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Optimal Planning of Smart Grid With Renewable Energy Resources

Naveen Jain, Jai Kumar Maherchandani, Navneet Kumar Agrawal, and Trilok Gupta

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Optimal Planning of Smart Grid With Renewable Energy Resources

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Growing awareness and an increased focus on environmental issues such as climate change, energy use, and loss of non-renewable resources have brought about a greater need for research that provides potential solutions to these problems. Research in environmental science and engineering continues to play a vital role in uncovering new opportunities for a "green" future.

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A method of optimization is used to resolve issues smartly by selecting the better option from various existing possibilities. Many optimization problems are possessing characteristics, namely nonlinearity, complexity, multimodal approach, and incompatible objective functions. Sometimes even for individual simple and linear type objective functions, a solution that is optimal and does not exist, there is uncertainness of obtaining the best solution. The aim of finding methods that can resolve various issues in a defined manner potentially has found the concentration of different researchers responsible for performing the advancement of a new "intelligent" technique called meta-heuristics technique. In the last few years, there is an advancement of various meta-heuristics techniques in different areas or various fields. Meta-heuristics are a demanded thrust stream of research that showed important advancement in finding the answer to problems that are optimized. The chapter gives the guidance for enhancing research more meaningfully.

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The small-scale wind energy generation system is one of the solutions to empower the isolated loads and provides a promising solution to decrease the greenhouse effect. This chapter describes the simulation analysis for wind energy conversion system incorporated with maximum power point tracking feature. The MPPT algorithms like variable current perturb and observe algorithm and variable step perturb and observe algorithm are incorporated with WECS. The comparative analysis is done in the closed-loop model in continuous time-varying wind speed. The closed-loop simulation is performed using a conventional fixed gain controller. To address the limitations of the fixed gain controller, the analysis is done using the gain scheduling proportional integral controller and the good gain method to tune the proportional integral controller. The comparative analysis between the fixed gain controller, the gain scheduling proportional integral controller, and the good gain method to tune proportional integral controller for above-stated MPPT methods is shown.

Application of multi-criteria decision analysis (MCDA) methods to various aspects of energy systems is of significant interest. This chapter first proposes a simple yet user-friendly MS-Excel tool with four popular MCDA methods. The tool can be effectively used to apply MCDA techniques and to determine the rankings for the alternatives. This MS-Excel tool is made available on Mendeley data repository. The chapter explains the overall MCDA computational processes, algorithms, and provides details on using the tool itself with the help of two case studies to demonstrate its effectiveness and applicability.

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Dairying has become a major secondary source of income for several rural families. The easily perishable nature of milk increases the spoilage of the product and reduces the dairy farms' productivity in rural areas due to power supply shortage issues. In order to overcome the inaccessibility of proper preservation strategies, this chapter proposed a hybrid DC-DC converter for a solar battery-powered milk vending machine. This proposed system can work continuously and provides an uninterrupted power supply to maintain the milk quality at an optimum level. Moreover, the proposed system utilized a novel converter to reduce the number of power conversion stages and compact the system. Besides, the proposed converter can achieve a higher gain ratio with fewer components. Furthermore, a proper algorithmic-based control scheme has been implemented to maintain effective power flow management. Finally, to verify the feasibility and performance of the system, detailed results are obtained at different dynamic conditions, and various case studies are presented in this chapter.

In this chapter, the author presents the operation and power management of the hydrogen storage-based smart DC microgrid (DCMG). In this microgrid, several renewable distributed generations (DGs) such as wind turbine, solar photovoltaic system, solid oxide fuel cell (SOFC), and battery energy storage system are interconnected together and to the various DC and AC loads to form a ring-type low voltage distribution network. An additional storage as Hydrogen storage system has been connected to the dc microgrid for balancing the power at all times in the DCMG, under islanded mode operation, for all practical cases. An architecture of the hydrogen storage-based DC microgrid is suggested mainly for the remote rural area. For the regeneration of the electricity from the stored hydrogen, a SOFC DG system is also used in the proposed DCMG. A control technique is also developed for the operation of the hydrogen storage-based DCMG. The proposed DCMG system provides a reliable and high-quality power supply and will supply the power to all loads (both DC and AC) simultaneously.

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Until the middle of 20th century, there was a strong conviction that the next century would be the age of renewable and nuclear energy resources. However, at present, the whole world is dependent on fossil fuels to satisfy their energy need. Environmental pollution and global warming are the main issues associated with the use of fossil fuels for electricity generation. As per the report of US Energy Information IE Outlook 2016, coal, natural gas, and petroleum share nearly 67.2% of global electricity generation whereas renewable energy shares only 21.9%. This share is only one-fifth of the global electricity demand. According to the IEA 2016 Medium Term Renewable Energy Market Report, worldwide power production capacity of marine was only 539 MW in 2014, and to reach at a level of 640 MW, it will take 2021. The oceans cover about 70% of the Earth and acts as the largest thermal energy collector. A recent study reveals that global development capability of ocean energy is approximated to be 337 GW, and more than 885 TWH of electricity can be produced from this potential.

In this chapter, the authors primarily discuss how blockchain is being utilized in smarter grids across the globe and how some use cases can be a good fit as a technology. They ensure the reliability and uninterrupted power supply to end users by using smart metering in micro and macro grids, which is possible with novel technology that is transparent and without any cyberattacks/hackers: blockchain technology (BCT). In this chapter, BCT is implemented significantly at micro/macro smart grid network. Such a network would give efficient improvement and be interesting.

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Foreword

The role of Renewable Energy Sources in the existing power systems has become vital. With greater emphasis on them, the power management becomes critical and challenging for successful operation of smart systems. Smart grid technology enables effective management and distribution of renewable energy sources such as solar, wind, oceans and hydrogen. The smart grid ties distributed energy resource resources to the power grid. This utilizes IoT to collect data on the smart grid enabling quick detection and resolving service issues through continuous self-assessments. In addition, optimal planning of resources is a must for reliable and cost-effective operation of the system considering the variability and availability of various resources including the storages, loads and serviceability of critical loads. In this backdrop a need was felt to come out with a detailed reference on planning of smart grid with renewable energy resources. I am happy that through this book a valiant attempt has been made to address these issues. This book includes all the key topics of the current trend in distribution system. Therefore, it is quite useful for post graduate students and research scholars. Further, this book fits for issues of global warming and climate change, mitigation of energy crises, dc-dc microgrid, application of advance controller, smart meters, smart grid, modern optimization approaches, renewable energy Integration in power system. Hence, it is a useful asset for post all those who are working in the fields of power system optimization, renewable energy integration and power electronics application in power system. The authors have contributed essence of their research work in the realm of the book in simple and lucid language. This book attempts to incorporate possible key requirements of power system, which can help in planning of an efficient grid.

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This book titled *Optimal Planning of Smart Grid With Renewable Energy Resources* is well edited by Dr. Naveen Jain, Dr. Navneet K. Agarwal, Dr. Jai Kumar Maherchandani and Dr. Trilok Gupta. They have scrupulously scrutinized the state-of-art towards meta-heuristic optimization techniques, analysis of advanced controllers, reliability aspects, and multi-criteria decision in energy system, hybrid dc-dc converters, dc micro-grid, ocean energy, smart meters, matrix converter, smart grid and renewable technologies in eight chapters. The book will serve as ready reference to the scholars and academicians. I convey my best wishes to all the contributors, the Editors and the Publisher.

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Preface

This book on *Optimal Planning of Smart Grid With Renewable Energy Resources* attempts to present the state-of-art work carried out towards meta-heuristic optimization techniques, analysis of advanced controllers, reliability aspects, multi-criteria decision in energy system, hybrid dc-dc converters, dc micro-grid, ocean energy, smart meters, matrix converter, smart grid and renewable technologies.

The optimal planning of renewable systems under different aspects and important issues are to be considered while carrying out studies related to the planning and operational aspects of a power system grid. The planning of the electric system with the presence of renewable energy requires the definition of several factors, such as the best technology to be used, the number and the capacity of the units, the best location, the type of network connection. The impact of renewable energy sources in system operating characteristics, such as electric losses, voltage profile, stability and reliability needs to be appropriately evaluated. Therefore, the use of an optimization method capable of indicating the best solution for a given distribution network can be very useful for system planning researches, when dealing with the increase of renewable energy's penetration that is rapidly increasing nowadays. The selection of the best places for installation and the preferable size of the renewable energy units in large distribution systems is a complex combinatorial problem.

This book also aims at providing a review of the relevant aspects related to renewable energy sources and impact that renewable energy sources might have on the operation of distributed networks. This book covers brief review of some basic renewable energy sources, current status of the technologies, potential advantages and disadvantages, review for placement of renewable energy sources, optimizations techniques/methodologies used in optimal planning in distribution systems. The goal of renewable energy integration is to enhance system planning, and operation of the electric grid to reduce carbon emissions and emissions of other air pollutants through increased use of renewable energy and other clean distributed generation resources.

Further, smart grid technology is enabling the efficient management and distribution of renewable energy sources such as solar, ocean, wind, and hydrogen with existing conventional energy sources. In the present domain of modern technology, a

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new trend of Internet of Things to collect data on the smart grid, utilities can quickly detect and resolve service issues through continuous self-assessment. In this book, attempt to incorporate all the key requirements of power system are considered, which help in planning of an efficient grid.

This book includes all the key topics of current trend in distribution system. Therefore, it is quite useful for postgraduate and research scholars. Further, this book fits in the following aspects of the global issues:

- Global warming and climate change.
- Mitigation of energy crises.
- DC-DC microgrid.
- Application of advance controller.
- Smart meters.
- Smart grid.
- Modern Optimization Approaches.
- Renewable energy Integration in Power System.

It is quite useful for postgraduate and research scholars, those who are working in the fields of power system optimization, renewable energy integration and power electronics application in power system.

A paragraph wise description of the importance of each chapter would give a wide understanding of this book.

In Chapter 1, titled "Different Meta-Heuristic Optimization Techniques and Their Application in the Solar Photovoltaic Field," a method of optimization is used to resolve issues smartly by selecting the better option from various existing possibilities. Many optimization problems are possessing characteristics namely nonlinearity, complexity, multimodal approach, and incompatible objective functions. Sometimes even for an individual simple and linear type objective functions, a solution that is optimal and does not exist, there is uncertainness of obtaining the best solution. The aim of finding methods that can resolve various issues in a defined manner potentially has found the concentration of different researchers, responsible for performing the advancement of a new "intelligent" technique called as meta-heuristics technique. In the last few years, there is an advancement of various meta-heuristics techniques in different areas or various fields. Meta-heuristics are a demanded thrust stream of research that showed important advancement in finding the answer to problems that are optimized. Chapter-1 gives the guilelines for carrying out research using heuristic approaches.

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In Chapter 2, titled "Comparative Analysis of Advanced Controllers for Standalone WECS for DC Microgrid Applications," it is emphasized that the small-scale wind energy generation system is one of the solutions to empower the isolated loads and provides a promising solution to decrease the greenhouse effect. The chapter-2 describes the simulation analysis-based Wind Energy Conversion System incorporated with the maximum power point tracking feature. The MPPT algorithms like variable current Perturb and Observe algorithm and variable step Perturb and Observe algorithm incorporated with WECS. The comparative analysis is done in the closed-loop model in continuous time-varying wind speed. The closed-loop simulation is performed using a conventional fixed gain controller. To address the limitations of the fixed-gain controller, an analysis is done using the Gain Scheduling Proportional Integral controller and the Good Gain method to tune the Proportional Integral controller. The comparative analysis between the fixed-gain controller, the Gain Scheduling Proportional Integral controller, and the Good Gain method is done to tune proportional integral controller for above-stated MPPT methods.

Chapter 3 is titled "A Novel MS-Excel Tool for Multi-Criteria Decision Analysis in Energy Systems." It is well-known factor that an application of Multi-Criteria Decision Analysis (MCDA) methods to various aspects of energy systems is of significant interest. This chapter proposes a simple, yet user-friendly MS-Excel tool with four popular MCDA methods. The tool can be effectively used to apply MCDA techniques and to determine the rankings for the alternatives. This MS-Excel tool is made available on Mendeley data repository. The chapter explains the overall MCDA computational processes, algorithms and provides details on using the tool itself with the help of two case studies to demonstrate its effectiveness and applicability.

Chapter 4 is titled "Design and Development of Hybrid DC-DC Converter for Solar-Battery-Based Standalone Milk Vending Machine." Dairying has become a major secondary source of income for several rural families. The easily perishable nature of milk increases the spoilage of the product and reduces the dairy farms' productivity in rural areas due to power supply shortage issues. To overcome the inaccessibility of proper preservation strategies, this chapter proposed a hybrid DC-DC converter for a solar battery-powered milk vending machine. This proposed system can work continuously and provides an uninterrupted power supply to maintain the milk quality at an optimum level. Moreover, the proposed system utilizes a novel converter to reduce the number of power conversion stages and compact the system. Besides, the proposed converter can achieve a higher gain ratio with fewer components. Furthermore, a proper algorithmic-based control scheme has been implemented to maintain effective power flow management. Finally, to verify the feasibility and performance of the system, detailed results are obtained at different dynamic conditions, and various case studies are presented in this chapter.

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Chapter 5 is titled "Operation of Hydrogen Storage-Based Smart DC Microgrid." In Chapter 5, the author presents operation and power management of the hydrogen storage based smart DC Microgrid (DCMG). In this microgrid, several renewable Distributed Generations (DGs) such as wind turbine, solar photovoltaic system, Solid Oxide Fuel Cell (SOFC), and battery energy storage system are interconnected together and to the various dc and ac loads to form a ring-type low voltage distribution network. An additional storage as Hydrogen storage system has been connected to the dc microgrid for balancing the power at all time in the DCMG, under islanded mode operation, for all practical cases. Architecture of the hydrogen storage-based dc microgrid is suggested mainly for remote rural area. For the regeneration of the electricity from the stored hydrogen, a SOFC DG system is also used in the proposed DCMG. A control technique is also developed for the operation of the hydrogen storage based DCMG. The proposed DCMG system provides reliable and high-quality power supply and will supply the power to all loads (both dc and ac), simultaneously.

Chapter 6 is titled "Ocean Energy: An Endless Source of Renewable Energy." It was a strong conviction that this century will be the age of renewable and nuclear energy resources. However, at present, the whole world is dependent on fossil fuel to satisfy their energy need. Environmental pollution and global warming are the main issue associated with the use of fossil fuel for electricity generation. As per the report of US energy Information IE outlook 2016, coal, natural gas and petroleum shares nearly 67.2% of global electricity generation whereas renewable energy shares only 21.9%. This share is only one-fifth of the global electricity demand. According to the IEA 2016 medium-term renewable energy market report, worldwide power production capacity of marine was only 539 MW in 2014 and to reach at a level of 640 MW, it will take 2021. The oceans cover about 70% of the earth and acts as the largest thermal energy collector. A recent study reveals that the global development capability of ocean energy is approximated to be 337 GW and more than 885 TWH of electricity can be produced from this potential. Hence, this chapter gives a wide perspective about ocean energy as potential renewable source.

In Chapter 7, titled "Real-Time Monitoring the Smart Meters Based on Blockchain Technology: RTM, the Smart Meter Based on BCT," the authors primarily discuss how blockchain is being utilized in smarter grids across the globe and how some use cases can be good fit as a technology. Ensure the reliability and uninterrupted power supply to end-users by using smart metering in micro and macro grids possible with novel technology and which has to be transparent without any cyber-attacks/hackers is blockchain technology (BCT). In this article, BCT implemented significantly at micro/macro smart grid network, where cumulative such network give efficient improvement would be quite interesting.

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In Chapter 8, titled “Matrix Converter: A Solution for Electric Drives and Control Applications,” the matrix converter (MC) has recently attracted significant attention among researchers because of its applications in wind energy conversion, military power supplies, induction motor drives, etc. Recently, different MC topologies have been proposed and developed which have their own advantages and disadvantages. Matrix converter can be classified as direct and indirect structures. This chapter aims to give a general description of the basic features of a three-phase to three-phase matrix converters in terms of performance and technological issues. Matrix converter is a direct AC-AC converter topology that can directly convert energy from an AC source to an AC load without the need of a bulky and limited lifetime energy storage element. AC – AC topologies that receive extensive research attention for being an alternative to replace traditional AC-DC-AC converters in the variable voltage and variable frequency AC drive applications.

This book will impact all the important dimensions of the power system as it covers detailed information of optimization technique, issues such as voltage sag and swell, VAR control, communication network modelling, power quality, protection and reliability are addressed judiciously for Renewable Energy Integration in Power System. As mentioned in above chapter wise discussion, it is clear that it would hopefully contribute in solving many issues of modern power system and will be helpful for the students and academicians.

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Introduction

In the present era, the availability of electricity to everyone is a key issue for researchers for sustainable development of a nation. The whole world is facing a challenge of continuously increasingly demand of electrical energy. The coal reserves are depleting at an alarming rate and affected with heavy raining at coal mines. In 2021, India and many other countries have been under shortage of coal for their coal fired power plants. Further, the coal fired plants have several health and environment related hazardous effects on the atmosphere. According to researchers, it was a strong conviction that this century will be the age of renewable and nuclear energy resources. However, at present, the whole world is dependent on fossil fuel to satisfy their energy need. Environmental pollution and global warming are the main issue associated with the use of fossil fuel for electricity generation. As per the report of US energy Information IE outlook 2016, coal, natural gas and petroleum shares nearly 67.2% of global electricity generation whereas renewable energy shares only 21.9%. This share is only one fifth of the global electricity demand. According to the IEA 2016 medium term renewable energy market report, worldwide power production capacity of marine was only 539 MW in 2014 and to reach at a level of 640 MW, it will take end of 2021.

These challenges can be reduced by maximizing the integration of Renewable Energy Resource (RES) in exiting power system. The RESs are clean and green source of energy and everlasting. Therefore, the increased use of the RES can mitigate the problem of supply demand deficiency and environmental issues. While dealing with the integration of RES in power system network, several issues take place like optimal placement and size of RES, cost effectiveness, voltage profile of the network, power loss, power electronics converters and controllers etc. All these requirements need to be addressed properly to get the maximum benefits from the RES towards making a Smart Grid.

In fact, there is always an acute need of suitable optimization procedure while planning of any subject matter as it is always a tedious task due to several available non-optimal options towards nonlinearity, complexity, multimodality and incompatibility in objective functions. It is important to notice that a non-optimal

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planning results lots of long lasting techno-economic challenges. In past, there has been lots of advancement in heuristics techniques in different areas with an aim of finding methods that can resolve various issues in a defined manner potentially. Hence, this book presents description of various meta-heuristic optimization techniques and its potential in power system to mitigate the thirst of the planning engineers for carrying out more meaningfully planning considering field constraints.

It is well known that technology updates of advanced controllers for standalone WECS for dc microgrid applications is not easily available. It calls for a comparative study for suitable selection of the controller for small-scale wind energy generation system to empower the isolated loads and provides a promising solution to decrease the greenhouse effect. Moreover, researchers always have an expectation of a simulation analysis-based Wind Energy Conversion System, maximum power point tracking feature, Perturb and Observe algorithm, comparative analysis (closed-loop model in continuous time-varying wind speed), limitations of the fixed gain controller, proportional integral controller and the Good Gain method for their study. In nutshell, this book gives guidance in design and operation of advanced controllers for integration of WECS in power system to form a DC microgrid.

Multi-Criteria Decision Analysis (MCDA) methods is of significant interest to various aspects of energy systems. Hence, this book incorporates a simple, user-friendly MS-Excel tool with four popular MCDA methods. The tool can be effectively used to apply MCDA techniques and to determine the rankings for possible alternatives. The book explains the overall MCDA computational processes, algorithms and provides details on using the tool. Further, it also represents the effectiveness of MS-office tool in the research and analysis for Multi-Criteria-Decision-Analysis in Energy Systems.

This book includes the application aspects of the RES and describes the Design for Development of Hybrid DC-DC Converter for Solar-Battery based Standalone Milk-Vending Machine to overcome the inaccessibility of proper preservation strategies. Furthermore, an algorithmic-based control scheme has been presented to maintain effective power flow management to verify the feasibility and performance of the system at different dynamic conditions for various case studies.

This book also includes the fuel-cell technology to make the environment greener and cleaner. Moreover, a new and less commercialized RES technology (Ocean Energy) is covered with its variants and technologies. The oceans cover about 70% of the earth and acts as the largest thermal energy collector. A recent study reveals that global development capability of ocean energy is approximated to be 337 GW and more than 885 TWH of electricity can be produced from this potential. This book also deals with the benefits and shortcomings of all ocean energy technologies with the power extraction techniques.

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The block-chain is being utilized in smarter grids across the globe to ensure the reliability and uninterrupted power supply to end users by using smart metering in micro and macro grids possible with novel technology and which has to be transparency without any cyber-attacks/hackers is block-chain technology (BCT). In this book, the BCT implemented significantly at micro/macro smart grid network, where cumulative such network give efficient improvement would be quite interesting for the readers. Additionally, it describes the BCT for smart metering including real time monitoring as a back bone of Smart Grid. This is the most needful metering aspects in the present scenario due to the inclusion of RES in hybrid mode.

Further, the matrix converter (MC) has recently attracted significant attention among researchers because of its applications in wind energy conversion, military power supplies, induction motor drives, etc. Recently, different MC topologies have been proposed and developed which have their own advantages and disadvantages. This book aims to give a general description of the basic features of a three phase to three phase matrix converters in terms of performance and technological issues. Matrix converter is a direct AC-AC converter topology that is able to directly convert energy from an AC source to an AC load without the need of a bulky and limited lifetime energy storage element. AC – AC topologies that receive extensive research attention for being an alternative to replace traditional AC-DC-AC converters in the variable voltage and variable frequency AC drives applications.

In a nutshell, this book can be considered as ready reference to get the idea about smart grid, DC microgrid, smart meter, renewable energy technologies, power electronics converters and controllers. This book is presented by observing an acute need to server above cited key points in power system at a single place in form of a book. The editors love to seek feedback from the readers for improving next edition of the book.

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Chapter 1
Different Meta-Heuristic Optimization Techniques and Their Application in Solar Photovoltaic Field:
A Renewable Energy Source

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ABSTRACT

A method of optimization is used to resolve issues smartly by selecting the better option from various existing possibilities. Many optimization problems are possessing characteristics, namely nonlinearity, complexity, multimodal approach, and incompatible objective functions. Sometimes even for individual simple and linear type objective functions, a solution that is optimal and does not exist, there is uncertainness of obtaining the best solution. The aim of finding methods that can resolve various issues in a defined manner potentially has

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found the concentration of different researchers responsible for performing the advancement of a new "intelligent" technique called meta-heuristics technique. In the last few years, there is an advancement of various meta-heuristics techniques in different areas or various fields. Meta-heuristics are a demanded thrust stream of research that showed important advancement in finding the answer to problems that are optimized. The chapter gives the guidance for enhancing research more meaningfully.

INTRODUCTION

Two real models namely single-diode (SD) as well as a double diode (DD) are the two most widely used models in practice with respect to solar cell analysis. The I-V characteristic that represents solar cell behavior is considered for the mathematical model. The core parameters that depict the PV module performance are the photocurrent, reverse saturation current, the diode ideality factor, shunt resistance, and series resistance. Meta-heuristic algorithms are exploited to get five parameters of the SD model and seven parameters of the DD model by minimizing proposed cost functions. Some Researchers used root mean square error (RMSE) as a cost function, which requires the calculation of the variance between measured and estimated current values. The researchers applied different meta-heuristic algorithms to minimize the RMSE.

In general, the modeling of a photovoltaic module involves the use of the I-V characteristic of a specific model under well defined environmental conditions. The design of models that can estimate parameters in a truly representative way remains a complex task. Indeed, the modeling depends on various factors namely the multitude of PV cell types including the number of diodes, shunt resistance, ideality factor as well as the most appropriate numerical methods.

It can be seen in figure. 1, that the solar cell under illumination is modeled as a current source, a diode, and two resistors. The shunt resistor represents the leakage current, and the series resistor denotes the resistance in the path of the current including electrode resistance, contact resistance, and material bulk resistance. However, a single diode model has inherent drawbacks as it assumes the diode ideality factor remains constant throughout the output voltage variation range. In this research study, 27 different meta-heuristic algorithms have been analyzed and compared for SDM, while 29 algorithms

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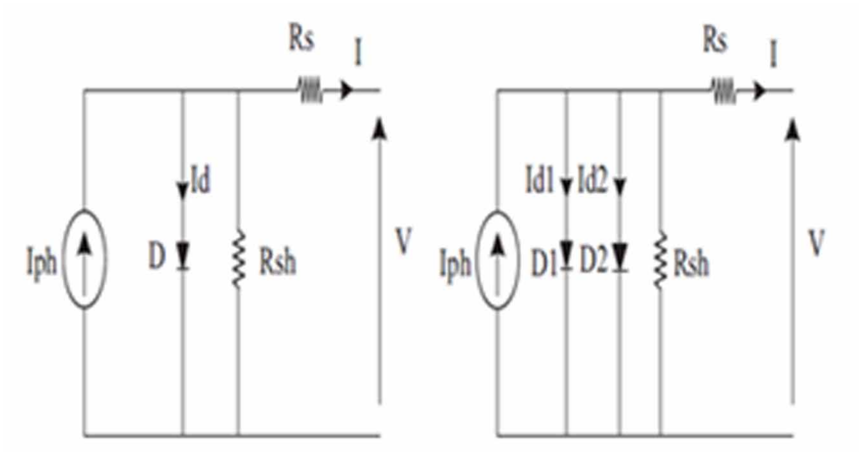
analyzed and compared for DDM. Best optimum parameters in SDM and DDM have been exploited under this study, which finds important for most of the researchers in the solar photovoltaic field for accurate estimation.

Figure 1. Equivalent electrical circuit of a solar cell; (a) SDM (b) DDM



BACKGROUND

Most engineering issues can be formulated as optimization problems. Optimization operation is generated enhance output with restricting sources by choosing the better, from a collection of existing possible solutions. Hussain et al., (2019) can use technique for optimization on potential spots at which the probability of finding diamond observed much more. In same manner, intelligent approach is achieved rather than laborious approach. The shortcomings of classical techniques, with respect to real time optimization issues, can be overcome using this heuristic approach. In this scenario, meta-heuristics methods will provide optimality, precision or complete solution in the terms of less time in order to find an approximate solution where traditional methods not able to give an exact solution. Fausto et al., (2020) proposed stochastic method based on integration of randomness in terms of optimization process, having advantages like problem formulation is less dependent and this method explore a problems design space thoroughly, so can find local optima more efficiently. The word heuristic obtained from the Greek term heuriskein which indicate to discover a goal using trial

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and error method. So heuristics are approximate technique which finds the solution space for determining a good result. Heuristics algorithms are sub classified into constructive and local searching technique. Constructive type method give an answer by connecting pieces of a result or solution, which are considered till the completeness in result is achieved. In Local type searching method, current solution tries to enhancing its components by modifying few of them. The Greek word ''Meta'' means beyond or above in a superior level. So, meta-heuristic is technique which clubbing heuristics in a general framework. Meta-heuristics methods are used for finding search spaces by considering different aspects in which a dynamic balancing is maintain between the exploitation as well as the exploration. It is important to quickly find the area in the searching space along with better or optimal solutions in less time in exploring search area which is not showing good quality solution. The modeling depends on various factors of PV cell types including the number of diodes, shunt resistance, ideality factor as well as the most appropriate numerical methods.

Various parameters in SDM and DDM have been exploited under this study, which finds important for most of the researchers in the solar photovoltaic field for accurate estimation.

1. Definition of Optimization

Optimization problem, named as P, is expressed as: $P = (S, \Omega, f)$ and S called as the searching space of decision variables with respect to a finite set X_i, $i = 1, \ldots, n$; Ω related to constraints out of the variables which used for taking the decision; f is called as objective function which undergo optimization.

To extend P, an optimal solution S*can expressed with minimum or reduced objective function Value $f(S^*) \leq f(s)$, $\forall s$ belongs to S, or $f(S^*) \geq f(s)$, $\forall s$ belongs to S, in order to maximized the function. Optimization concept differentiates as individual type or as multi objective type constrained, unconstrained, or combinatorial form proposed by Bianchi et al., (2009).

2. Optimization Models

Optimization methods are employed in order to get the decision variables values in which objective function tends to optimize under certain constraints. As scientists or an engineer, or a manager, always have to take decisions.

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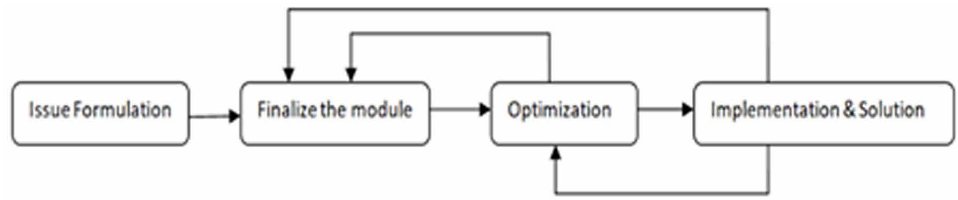
Figure 2. Optimization model



- Formulation of the issue
- Model the problem
- Optimize the problem
- Implement a solution

3. Definition of Meta-Heuristics Optimization

In searching process a system of finds solutions to the problem using a various rules as well as mathematical equations by considering multiple iterations, till predefined criterion were meet. So obtained result which is closer to near optimum is called as an optimal result found by Dilip & Kaushik, (2017). Meta-heuristic techniques (M) will be explained as: $M = (O, A, R_c, R_i, R_o)$ here, O is collection of heuristic techniques, it may be meta-heuristic, automotive type, trial error, adaptive cognitive. A is related to generic method, $R_c = O \times A$, which shows the collection of internal relationship and R_i is a collection of input things. Ro is a collection of output relations.

4. Need of Meta-Heuristic

A meta-heuristic is a heuristic type in which various can solve without changing the original framework of algorithms. Meta-heuristic methods obtained best solution by performing iteration process. Using this method the best or optimal solutions can be obtained even though problem size is large and required less time. Using it, researcher can find good solutions quickly in a restricted area with respect to local search. Global optimal solutions can be found in the systematic and efficient ways. Although meta-heuristics techniques cannot always provide the true global best solution, but it can give very good results for various practical issues. It can enhance the power of computing of a computer system greatly by not increasing the hardware cost.

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5. Meta-Heuristics Optimization Key Factors

In Meta-heuristics techniques key factors; namely neighborhood search along with diversification and exploration or intensification and exploitation or local and global minima as well as search, escaping local minima, evolutionary computing, as well as swarm intelligence, etc has to consider. Along with this, maintaining balance among exploration and exploitation, finding most potential neighbors, rejecting inefficient neighbors, and limiting searching process for unpromising neighbors have to be considered.

a. Exploration and Exploitation

Explorations versus exploitation are called as diversification-intensification, divergence- convergence respectively which is mark able features of method of optimization found in Kaveh & Seddighian, (2020). Exploration is a capability to expand searching process in distributed domain so that anyone can find out unvisited areas, where as process of exploitation, allows concentrating promising regions to get good or optimum solutions to optimally convergence.

b. Local and Global Search Meta-Heuristics

Local searching methods are exploitative type methods. Examples are tabu searching, greedy randomized type adaptive searching etc. Whereas a global searching techniques are explorative type. Examples are ant colony method, genetic algorithms, particle swarm optimization etc. Hybrid methods also exist.

c. Intensification and Diversification

Diversifications related to generating diverse solutions in order to find the searching space, where as Intensification related to focusing the finding in the local area that assumed a current optimal solution can be obtained within this region.

d. Meta-Heuristic Algorithm Properties

Meta-heuristics techniques posses the following properties:

- Meta-heuristics guides the searching process.

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- Near optimal solutions can be finding efficiently by exploring the searching space.
- It ranges from easy local to complex searching learning procedure.
- It follows approximation and generally stochastic.
- Design patterns for developing new meta heuristic techniques:

With respect to the collected primary data, design patterns or the metaphors are considered from various disciplines which shown in figure 3. Mostly heuristics are bio dependent, or from regular life; like, interior design, sports, or vocational stream etc. Number of metaphors has obtained from the area which related with humans rule dependency as well as move economic systems, by considering Economics and area of Military.

Figure 3. Metaphor for designing meta-heuristics concept

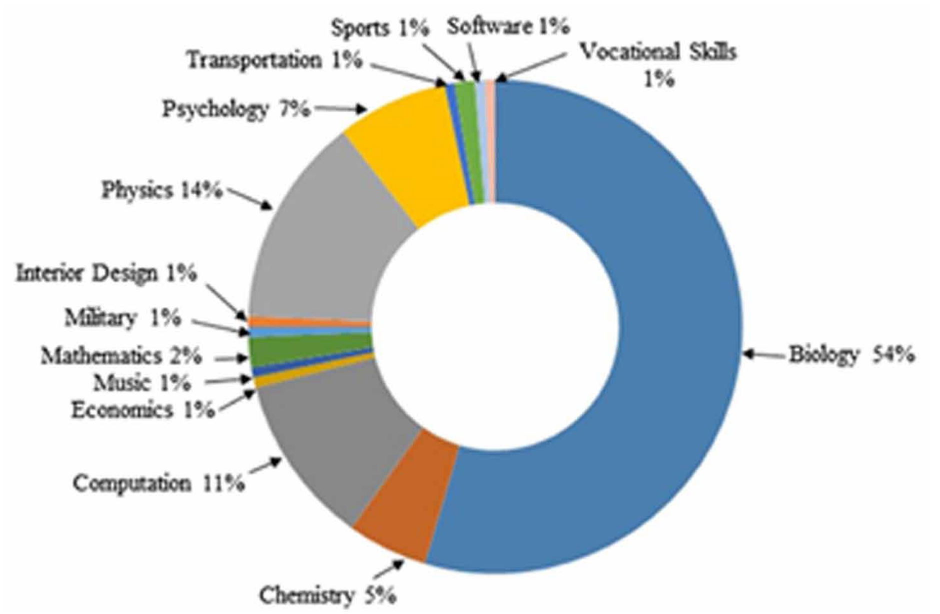

Figure 3 Show leading metaphors normally preferred by research scholar. Among these, insect's social behavior is considered to design efficient optimization technique. In insect families, bees and ants behavior are used. Along with it, the biological actions of Glow Fly, spiders, and microbes are used in proposing powerful meta-heuristics. Darwin theory of survival is considered for same.

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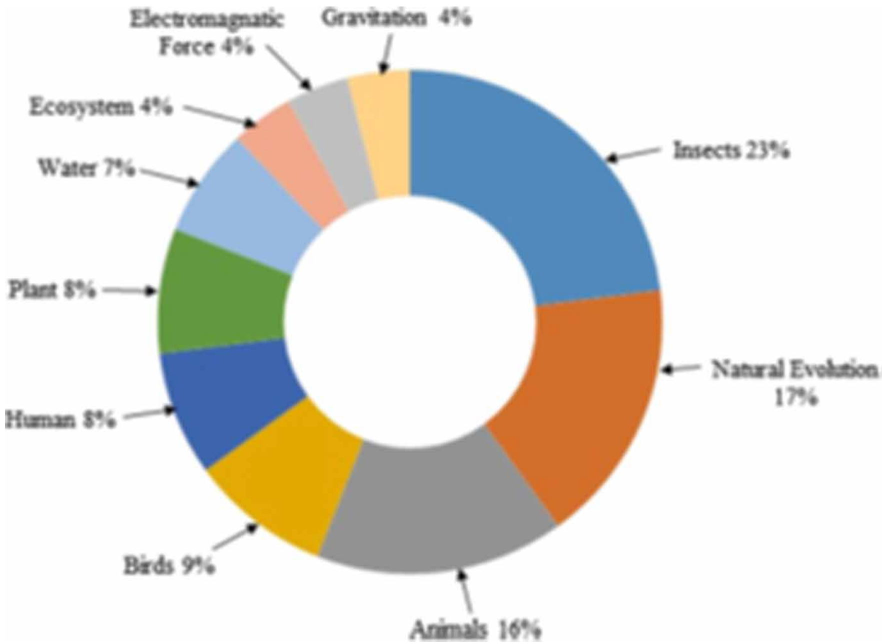
Figure 4. Metaphors for designing new meta-heuristics concept



6. Meta-Heuristics Optimization Classification

Different heuristics share the important characteristics like inspiration from nature, they utilize stochastic components concept considering random variables, and they cannot use the concept of gradient matrix for objective function explained by Sorensen et al., (2018). It possesses a number of properties in order to classify them.

a. Nature inspired and non nature inspired: Various heuristics are originated by natural stages namely evolutionary, unnatural immune systems, bee's behavior, and optimization based on swarm intellect etc.
b. Memory usage versus memory less methods: Memory less means, no information retrieved during the searching stage. For examples local search. Whereas memory usage method uses valuable information obtained online due to the process of searching. It may be short or long term memories which can be used in tabu type searching.
c. Deterministic and stochastic: A deterministic type makes deterministic decisions for example local searching or tabu searching. Whereas in stochastic, various rules are considered during the searching process like

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simulated annealing method or evolutionary method. In deterministic type techniques, same initial conditions will give the same final conditions or solution, where in stochastic type method; various end solutions may be getting from same starting condition or solution.

d. Population and single solution type searching: Single solution methods for e.g. local searching or annealing can forward only one solution in searching process where in population based methods namely, swarm or evolutionary methods, a entire population is considered.
e. Local search versus Global search: Local search will improve the solutions. Examples for the same are annealing, tabu. Global search techniques are usually population dependent methods. It contains ant optimization method, evolutionary computation, swarm method, genetic method etc.
f. Hybridization and mimetic algorithms: A hybrid method combines a other optimization methods or approaches like algorithms from applied mathematical, constraint concept, machine learning concept. With respect to Memetic algorithms, individual learning for problem searching is considered.
g. Iterative and greedy: Iterative method starts with solutions related to population and transformation taking place at individual iteration by considering some searching operators. Greedy method initiate using a blank solution, a decision variable is assigned at every step till a entire solution is generated.

7. Meta-heuristics Optimization Algorithms

Various meta-heuristic algorithms can be considered so those to retrieve best fitness function.

a. Single solution dependent meta-heuristics: It's referred as an ''intelligent'' extensions of local searching methods, which includes the simulated type annealing technique, tabu searching, the GRASP technique, variable neighborhood searching, guided local searching, iterated local searching, and variants related to it.
    i. Simulated annealing (SA):

Simulated type annealing technique was first explained by Kirkpatrick et al., (1983). In this method the objective function is to be optimum, by initiating a temperature called as fictitious denoted by T, controlling term of the method.

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It started by producing a starting solution also by defining the parameter of temperature T. After this, at every iteration, solution named as S' is choose abruptly in neighborhood named as N(s) with respect to present solution S. The S' is considered as new defined solution depend upon T, objective function related to S' and S, are represented by f(S'), f(S), respectively.

- Microcanonic annealing (MA):

MA is a variant of simulated type. SA uses main a Metropolis algorithm but Microcanonic annealing concentrate on the Creutz method, called as demon techniques (Creutz, 2013). The technique accepts all disturbances result in the movement close to lower states of energy, by adding departed potential energy into kinetic energy. Microcanonic annealing method is mentioned in Algorithm 2. At every energy stage, an equilibrium stage is achieved once the ratio of the average or mean kinetic type energy find to deviation in terms of distribution is near to 1.

Algorithm 1: SA Algorithm:

1 Choose, at random, an initial solution s for the system to be optimized
2 Initialize the temperature T
3 while the stopping criterion is not satisfied do
4 repeat
5 Randomly select s' E N(s)
6 if f(s') ≤ f(s) then
7 s ← s'
8 else
9 s ← s'with a probability p (T, f(s'), f(s))
10 end
11 until the "thermodynamic equilibrium" of the system is reached
12 Decrease T
13 end
14 return the best solution met

Algorithm 2: MA Algorithm:

1 Choose, at random, an initial solution s for the system to be optimized
2 Initialize the kinetic energy E,
3 repeat
4 repeat
5 Randomly select s' Ɛ N(s)

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6 Calculate $\Delta E = f(s') — f(s)$
7 if $\Delta E < Ec$ then
8 $S \leftarrow s'$
9 $Ec \leftarrow Ec - \Delta E$
10 end
11 until the "thermodynamic equilibrium" of the system is reached
12 Decrease Ec
13 until Ec is close to 0
14 return the best solution met

- Threshold accepting method (TA):

Simulated annealing acquire a result which causes degradation of the objective function only with specific probability; whereas, Threshold accepting mentioned by Dueck & Scheuer, (1990) take up this solution if and only if the deterioration of function will not crosses a progressively reducing threshold value named as T. Method is described in Algorithm 3.

Algorithm 3: TA Algorithm
1 Choose, at random, an initial solution s in the search space
2 Initialize the threshold T
3 repeat
4 repeat
5 Randomly select $s' \in N(s)$
6 Calculate $\Delta f = f(s') — f(s)$
7 if $\Delta f < T$ then
8 $s \leftarrow s'$
9 end
10 until the best solution met is not improved for a certain duration, or a given number of iterations is reached
11 Decrease T
12 until T is close to 0
13 return the best solution met

- Noising method (NM):

Charon & Hudry, (1993) defined the noising method. Initially suggest for the clique compartmenting issues in a graph. Using a local searching technique, initialization of initial solution taking place, and then carries out

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improvements in number of iteration till a local optimum can obtain. During individual iteration of method, noising amplitude related to objective function reduces till come very closer to zero. So that it avoid local optimum issue if exist.

Algorithm 4: NM Algorithm

1 Choose, at random, an initial solution in the search space
2 Initialize the amplitude of noise
3 repeat
4 Add noise to the objective function
5 Apply local search to the "perturbed" objective function, starting from the current solution
6 Decrease the amplitude of noise
7 until the amplitude of noise is zero
8 return the best solution met

ii. Tabu search (TS):

It was elaborated in the year 1986 by Glover et al., (1986). It prepared to handle an embedded type local searching technique. It utilizes the history related to searching process, to avoid from local minimum and also to design an explorative way strategy. This was inspired by the human being memory, so can learn using the past experience. Different memory formats are considered to remember particular characteristics of orientation through searching space that the method has undertaken.

Algorithm 5: TS Algorithm

1 Choose, at random, an initial solution s in the search space
2 TabuList$\leftarrow\phi$
3 while the stopping criterion is not satisfied do
4 Select the best solution s' Ɛ N(s) \ TabuList
5 s ← s'
6 Update TabuList
7 end
8 return the best solution met

iii. Greedy Randomized Adaptive Searching Procedure (GRASP) Method:

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It is a type of multi start heuristic without memory methods for optimization problems, formulated by authors Feo & Resende, (1989). Every iteration divided into two main steps namely construction step and local searching step. The construction stage put up solution which is feasible in nature by considering randomized greedy method. Then solution is utilized as a starting solution of local searching method. Then it is ended and better or optimum solution is obtained. At individual iteration every element is included in solution retrieved partially without destroying feasibility, till a complete solution is obtained using Algorithm 6.

Algorithm 6: GRASP Algorithm:

1 Build a feasible solution using a randomized greedy heuristic
2 Apply a local search starting from the built solution
3 until the stopping criterion is satisfied
4 return the best solution met
5 repeat

iv. Variable neighborhood searching (VNS):

VNS was put forward by Hansen, Mladenovic, (1995). It involves the exploration of continuously varying neighborhoods for specific or particular solution. At first, a group of neighborhood formation has to be defined. VNS cycle made up of 3 steps namely shaking, searching in local area and moving. Firstly shaking stage will come in which an initial solution is choose abruptly in nth neighboring of the present solution named as s. Now, first solution denoted as s0 is called as starting solution of local searching steps, to propose the final s00 solution. After most of the local searching steps, if solution s00 is superior as compared to s, then this solution return and this cycle reinitialize with value n is equals to 1. If not, then the methods witch to the succeeding neighborhood n +1and then a new stage of shaking initializes using neighborhood.

Algorithm 7: VNS Algorithm:

1 Select a set of neighborhood structures Nn, n = 1,…….., nmax
2 Choose, at random an initial solution s in the search space
3 while the stopping criterion is not satisfied do
4 n ← 1
5 while n <nmax do
6 Shaking: select a random solution s' in the nth neighborhood Nn(s) of s

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7 Apply a local search starting from s' to get a solution s"
8 if s" is better than s then
9 s ← s"
10 n ← 1
11 else
12 n ← n+1
13 end
14 end
15 end
16 return the best solution met

v. Guided local search (GLS):

Voudouris, (1997) proposed guided LS, memory is named an augmented function. First, a group of features must be defined. Individual feature tells about a aspect of a solution with respect to various optimization issues to solve. Then, cost denoted by c_i as well as a penalty value denoted pi are bounded along with every feature.

Algorithm 8: GLS Algorithm:
1 Select a set of features ftn, n = 1, ……,nmax
2 Choose, at random, an initial solution s in the search space
3 Initialize the penalties pi to 0
4 repeat
5 Apply a local search starting from s to get a solution s, using the augmented objective function*
6 for each feature fti of s do*
7 Compute the utility uioffti
8 end
9 j ←arg maxi=1nmaxui
10 pj←pj +1
11 until the stopping criterion is satisfied
12 return the best solution met

vi. Iterated local search (ILS):

Rather than continuously using a local searching step to abruptly generate starting result, iterated local search provides the initial solution utilized for the succeeding iteration by perturbing a local optima which found at current

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cycle or iteration. The perturbation concept is a main feature of ILS. ILS technique was described by Stutzle, (1998) mentioned in Algorithm 9. In which the acceptance measures defines the detail conditions.

Algorithm 9: ILS Algorithm

1 Choose, at random, an initial solution s in the search space
*2 Apply a local search starting from s to get a solution s**
3 repeat
4 Perturb s to get a solution p*
*5 Apply a local search starting from p to get a solution p**
6 if the acceptance criterion is satisfied then
7 s← p**
8 end
9 until the stopping criterion is satisfied
10 return the best solution met

b. Population based meta-heuristics:

It deals with a population rather than a single solution. They are correlated to Evolutionary Computation method abbreviated as EC as well as Swarm Intelligent abbreviated as SI. Evolutionary methods are obtained from the Darwin's concept, and population is changes by using operators namely recombination as well as mutation proposed by Peska et al., (2019).

i. Evolutionary computation:

It is stimulated by Darwinian Theory of nature's ability to developed species well adjust to related surrounding or environment. In every iteration, individuals is able to reproduced and it is related to genetic variations go along with the surrounding pressure which responsible for natural selection called as survival or existence of fittest. Enhanced solutions are obtained by using recombination process, that recombines parents in order to produce the children or also called as offspring, as well as mutation, which allows the new attribute of the offspring in order to develop divergence.

Algorithm 10: EC Algorithm

1 Initialize the population with random individuals
2 Evaluate each individual
3 repeat

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4 Select parents
5 Recombine pairs of parents
6 Mutate the resulting offspring
7 Evaluate new individuals
8 Select individuals for the next generation
9 until a termination condition is satisfied

- Genetic Method (GA):

The Genetic method is frequently used evolutionary computation method. It deals with solution called as chromosomes, preference ways, type of different crossover as well as mutation director, etc. A fixed length binary string notation is mostly used. Concentration is mainly upon crossover and considered as major variation operator.

- Evolution Strategy:

It was proposed and extended by Rechenberg, (1965). Initially Evolution Strategy method, applied in the area of experimental optimization, and it was a simple mutation process selection said two member ES. This type of strategy is depending on a population made up of a one parent produces, in the terms of Gaussian type distributed mutation.

- Evolutionary programming (EP):

Evolutionary Programming was first elaborated by L. Fogel, (1988). Later, it was reintroduce by scientist D. Fogel, 1990 in order to answer more specific tasks considering forecast issue, numerical optimization, also steam of machine learning. This programming is not depending on any type of recombination process. Mutation is an operator which is used to reproduce new offspring. This is executed by summing an abrupt number of distributions into the existing parent.

- Genetic programming (GP):

GP proposed by Koza, 1992. In this type of programming, the each member of population is not constant or confirmed length strings represented as computer programs and then executed. It is a method which started from a population randomly programs, and fit for specific task by using operations

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equivalent to the natural genetic steps to the population of computer programs. The variables as well as constants present in program are named as terminals in genetic programming, are leaves, where the arithmetical operations are inner nodes also called as a functions. GP initialize with a starting population which are abruptly generated programs consist of functions, terminals approximate to the problem. The population is evolved over a number of generations, considering basis of Darwinian Theory, biologically motivates operations, considering crossover stage and mutation stage. Computer programs are selected on probability basis in order to obtain next population. Tournament selection and fitness proportionate methods are used for generating the next population. The frequently used form of mutation is sub tree type that randomly chooses a mutation area in a tree, also placed the sub tree rooted with abruptly generated sub tree. Another form of mutation stage involves single number node mutations as well as number of structure related to code editing in order to reject unwanted code or syntax from trees.

ii. Other evolutionary algorithm

Various forms of evolutionary methods are mentioned in the previous work. Among them, we can see the estimation related to distribution method, differentiable evolution, co evolutionary technique, ethnic method and Scatter Searching as well as track relinking.

- Estimation of distribution method: These methods are depend upon probabilistic models, in which genetic combination also mutation of GA can be changed by using two stages namely find individuals probability distribution and produce fresh population by using concept of probability distribution function. The obtained solutions are included to the original population, restoring few from previous ones or all. The process is continuing till the end or termination test is fulfilled. EDAs can be classified into three subclasses, namely univariate, bivariate, multivariate EDAs.
- Differential evolution method (DE): DE algorithm is popular for the continuous type global optimization issue. It was found by Storn & Price, (1997) to resolve Cheyshev polynomial problem related to fitting and used for optimization strategy for various tasks. For every generation, new individuals were generated by using reproduction process operators namely crossover operator as well as mutation operator. The ending individual is obtained by combining the target

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individually with other generated by mutation process individually. The mutation in the method is carry out by finding vector differences among abruptly considered individuals of same population. The important power of the DE method is requirement of less number of control parameters. Three input terms or parameters are used to control the searching process are nothing but the population size, constant of differentiation, the crossover controlling parameters.

- Co-evolutionary algorithms (CoEA): It was proposed Hillis, (1990). It is based on sorting networks. It is subdivided into two categories namely competitive and cooperative co-evolution. In Competitive type two populations will oppose the interests as well as the victory of one's rest on the unsuccessfulness of other. So fitness marks the relative power of solutions so an enhanced fitness with respect to solution tends to return the fitness for other. It happen still the optimal solution is achieved globally. Evolution of populations taking place simultaneously, separated or isolation from another, in order to obtained the perfect fitness. Some forms of Cooperative methods have been mentioned, such as CoEA's particle swarms, CoEA's DE.
- Cultural algorithms (CA): It is proposed by Reynolds and Fogel, (1994) that worked at a micro level with respect to transferring genetic information among themselves in a population as well as macro level with respect to the information obtained from individual experiences. Cultural algorithms have three components namely a Population Space, which keep a collection of individuals that has to obtained, the procedure for evaluation, replication, as well as modification. Second is a Belief Space, which explained about the knowledge that can be retrieved by population in the process. The important purpose is to maintain beliefs which are accepted at social level and reject which are not accepted. The framework of this algorithm is presented in Algorithm 11. In every generation, individuals are first evaluated using function (Evaluate ()). An (Accept ()) is tells that which one in the present population has to be enable in order to share with its information to belief space. It has to be added to the information of belief terms using function Update ().The functions Accept and the function Influence forms the communication path among space of population and the space of belief.

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Algorithm 11: CA Algorithm

1 Set the generation counter g= 0
2 Initialize the population (POP(g))
3 Initialize Belief Space (Beliefs(g))
4 repeat
5 Evaluate Population: Evaluate (POP(g))
6 Update(Beliefs(g), Accept(POP(g)))
7 Generate(POP(g), Influence (Beliefs(g)))
8 g=g+ 1
9 Select(POP(g) from POP(g-1))
10 to until a termination condition is achieved

- Scatter searching (SS), path relinking (PR): They were originally proposed in the years 1990s by researcher Glover, (1997).Both worked on principles used for connecting solutions based on track constructions or structure considering both Euclidean as well as neighborhood spaces and also by using strategic structure which uses concept of randomization. They have advantage like exploit adaptive memory. Space the methods work upon a collection of solutions, the reference set denoted as 'RefSet', by joining the same solutions to generate newer one. The method initiate by producing the initial group of vectors which satisfying diversity criteria. It can add to reference collection when diversity improves even though an objective function is inferior over other competing solutions.

Algorithm 12: SSPL Algorithm

1 Initial Phase:
2 SeedGeneration()
3 repeat
4 DiversificationGenerator()
5 Improvement()
6 ReferenceSetUpdate()
7 until The reference set is of cardinality n
8 Scatter Search/Path Relinking Phase:
9 repeat
10 SubsetGeneration()

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11 SolutionCombination()
12 Improvement()
13 ReferenceSetUpdate()
14 until a termination condition is achieved

c. Swarm intelligence (SI)

Swarm intelligence techniques made up of population of agents which interacted in local space with each other and also along with environment. They are stimulated by the metaphors of swarming nature. The various methods can come under this category and explain in detail in following subsections.

i. Ant colony method (ACO):

Ant Colony techniques were explained by Dorigo, (1992) which got the inspiration from nature to get the solution of hard optimization method. It's inspired from the nature of real ants. During food searching process, ants find out the area surrounding to nest initially by doing random walk. Along track followed in between food source as well as nest, an ant leaves a chemical substance pheromone fall on the route so that ant can mark favorable path that will be helpful to other in order to tell other ants for reaching towards food source. Finally, the shortest distance between nest and the food source presents is found.

Algorithm 13: ACO Algorithm
1 Initialize pheromone values
2 while termination condition not met do
3 Construct Ants Solutions
4 Update Pheromones
5 Daemon Actions
6 end

ii. Particle swarm optimization (PSO):

PSO method was proposed by Kennedy & Russell, (1995), as a one of important optimization method. It considered nature of flocking of birds to resolve issue related to optimization method. In PSO method various autonomous entities also named as particles which are created in searching area stochastically. Individual particle is represented by the velocity, search space

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with respect to a location and possess a memory that used in recollecting its old optimum position. The swarm is made up of N numbers particles present in dimensional searching space. Each particle followed a topology explains the interconnections between the particles. The two normally considered are called as gbest abbreviated as ''global best'' and second one is lbest abbreviated as ''local best''. gbest gives the information about the perfect and better neighbor in the whole group with respect to target particle. Initially, the positions as well as velocities of each particle are abruptly initialized.

Algorithm 14: PSO Algorithm

1 Initialize a population of particles with random positions and velocities on D dimensions in the search space while Terminating condition is not reached do
2 for each particle i do
3 Adapt velocity of the particle
4 Update the position of the particle
5 Evaluate the fitness f(Xi)
6 if (f(Xi) < f(Pi)) then
7 Pi←Xi
8end
9 if (f(Xi) < f(Pg)) then
10 Pg← Xi
11 end
12 end
13 end

iii. Bacterial foraging optimization algorithm (BFOA):

BFOA, proposed by Passino et al., (2002). It is recent method for resolving optimization issues. It is simulated by the nature of E. coli abbreviated as Escherichia coli bacteria exist in the human intestines. Various organisms are trying for searching and consuming nutrients in such way that it can enhance the energy retrieved through sources of nutrient per unit time spent foraging, also decreases risks from predators. Foraging in set is an important element in order to avoiding predators as well as maximizing the chance of searching food. Chemo taxis is procedure for directing the bacteria with respect to some chemicals in their surrounding or environment. The receptor proteins sensors are utilized for the same and that is very sensitive as well as possesses

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large gain. Swarming is motility type which is extended by using flagella. It enables bacteria movement fastly above the surfaces or between surfaces.

Algorithm 15: BFOA Algorithm

1 Initialize parameters: D, S, Nc, Nre,Ned, Ped, C(i), Θi (i = 1,2,……..,S)
2 while terminating condition is not reached do
3//Elimination-dispersal loop:
4 for l = 1,……..,Nre do
5 // Reproductionloop:
6 for k = 1,……..,Nre do
7 //Chemotaxis loop:
8 for j = 1,…….., Ncdo
9 for each bacterium i = 1,………..,S do
10 Compute fitness function J (i, j, k, I)
11 Jlast = J(i, j, k, l)
12 Tumble: Generate a random vector Δ(i)Ɛ RD
13 Move: Compute the position of the bacterium Θi (j + 1, k. I) at j+Ith chemotactic step
14 Compute fitness function J(i, j + 1, k, l)
15 Swim: m = 0 //counter for swim length
16 while m < Nsdo
17 m = m + 1
18 if J(i, j + 1, k, l) <Jlast then
19 Jlast = J(i, j + 1, k,l)
20 Move: Compute the position of the bacteriumΘi (j+ 1, k, l) at j+ Ith chemotactic step
21 Compute fitness function J (i, j + I, k, I)
22 else
23 m = Ns
24 end
25 end
26 end
27 end
28 Reproduction:
29 for i = 1,………..S do
30 Jhealth(i) = Σ J(i, j, k, l)
31 end

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32 sort bacteria in order of ascending Jhealth (higher cost means lower health). The least healthy bacteria die and the other healthier bacteria split each into two bacteria, which are placed in the same location
33 end
34 elimination – dispersal:
35 for I = 1,……………..,S do
36 eliminate and disperse the ithbacterium, with probability Ped
37 end
38 end
39 end

iv. Bee colony optimization technique (BO):

It is considered the nature of bee colony which possesses various features and can be taken into account as models for intelligently developed systems. It considers connection, food foraging, selection of task, collective decision building, selection of nest area, flight mating as well as coupling in the group of bee, floral lying way finding. In Marriage Bee colony optimization also called as MBO method, the mating flight can be related to a collection of switching in a the surrounding or environment in which queen movement taking place among the various states occupies in the space with specific speed and probabilistically mates with drone come across at every state described by Abbass, (2001).

Algorithm 16: MBO Algorithm
1 Initialize workers with some heuristic
2 Randomly generate the queens
3 Apply local search to get a good queen
4 for A pre-defined maximum number of mating-flights do
5 for each Queen in the queen list do
6 Initialize energy, speed and position
7 The queen moves between states and probabilistically chooses drones
8 if A drone is selected then
9 Add its sperm to the queen's spermatheca (i.e., a list of partial solutions)
10 end
11 Update the queen's internal energy and speed
12 end
13 Generate broods by crossover and mutation
14 Use workers to improve the broods

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15 Update workers' fitness
16 while The best brood is better than the worst queen do
17 Replace the least-fittest queen with the best brood
18 Remove the best brood from the brood list
19 end
20 end

Variants for the methods are Bee Colony Meta-heuristic abbreviated as BCO, Bee Colony method abbreviated as ABC, Virtual Bee method abbreviated as VBA. For ABC method there groups namely, employed bees named as forager type bees, onlooker type bees named as observer, scouts named as explorer are considered. Employed type bee flow the data related to food and with specific probability it transfers this information by waggle dance. Onlookers bees observe this waggle dancing and there for kept on food origin by considering a probability dependent selection steps. Once sufficient amount of a food origin enhances, probability related to food source by onlookers is also increases.

Algorithm 17: ABC Algorithm

1 Initialize Population
2 repeat
3 Place the employed bees on their food sources and determine their nectar amounts
4 Calculate the probability value of the sources with which they are preferred by the onlooker bees
5 Place the onlooker bees on the food sources depending on their nectar amounts
Stop the exploitation process of the sources exhausted by the bees
7 Send the scouts to the search area for discovering new food sources, randomly
8 Memorize the best food source found so far
9 until requirements are met

v. Artificial immune systems (AIS)

The resistant system prevents organisms from pathogens like bacteria, viruses without considering previous knowledge of their framework mentioned by Hart, (2011). The highly spreader, adaptive in nature, self organizing behavior gave rich metaphors an artificial counterpart. Also AIS try to use

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immune system objective in order to optimize the process and machine learning issues. Four main AIS algorithms are mentioned below:

- Negative Selection Based Algorithms.

It is explained by author Forrest et al., (1994) in order to find information manipulation resulted by a virus present in computer system.

Algorithm 18: NSA Algorithm

Input: S seen = set of seen known self elements
Output: D = set of generated detectors
1 repeat
2 Randomly generate potential detectors and place them in a set P
3 Determine the affinity of each member of P with each member of the self setSseen
4 if At least one element in S recognizes a detector in P according to a recognition thresholdthen
5 The detector is rejected
6 else
7 The detector is added to the set of available detectors D
8 end
9 until stopping criteria have been met

It is worked on principles of the own or self and non self inequity in immune system. Initially it is generate a number of self strings called as S, which explained the general state of the system. After this, collection of detectors is generated named as D, which only recognize the complement of S. For classifying own also named as self versus non self category, detectors are applied to new data. The negation selection method is elaborated in Algorithm 18.

- Clonal Selection Based Algorithms.

This method works on principle that repertoire of various B type tissues, which encoded antibodies along with a well defined structure or shape, is created earlier to any type of exposure with respect to antigen. Clonal expansion is taking place for selected B type group along with antibody conduit having the capability of interacting with portion of antigen.

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Algorithm 19: CSA Algorithm

Input: S = set of patterns to be recognized, n the number of worst elements to select for removal output: M = set of memory detectors capable of classifying unseen patterns

1 Create an initial random set of antibodies A

2 for all the Patterns in S do

3 Determine the affinity with each antibody in A

4 Generate clones of a subset of the antibodies in A with the highest affinity. The number of clones for an antibody is proportional to its affinity

5 Mutate attributes of these clones inversely proportional to its affinity.

6 Add these clones to the set A, and place a copy of the highest affinity antibodies in A into the memory set M

7 Replace the n lowest affinity antibodies in A with new randomly generated antibodies

8 end

- Artificial Immune Networks (aiNet)

Immune Network concept was expressed by Jerne, (1973). It tells that immune system or structure is a considered antibody, B type cells s well as T type cells. It recognize foreign to the body as well as forming a structure wise and function wise network of cells and alter to stimuli with respect to time factor. It tells the information about the interactions among cell, memory and other functions namely tolerance and reactivity.

Algorithm 20: AIN Algorithm

Inputs: S = set of patterns to be recognized, nt network affinity threshold, ct clonal pool threshold, h number of highest affinity clones, a number of new antibodies to introduce

Output: N = set of memory detectors capable of classifying unseen patterns

1 Create an initial random set of network antibodies, N

2 repeat

3forall the Patterns in S do

4 Determine the affinity with each antibody in N

5 Generate clones of a subset of the antibodies in N with the highest affinity. The number of clones for an antibody is proportional to its affinity

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6 Mutate attributes of these clones inversely proportional to its affinity, and place the h number of highest affinity clones into a clonal memory set C
7 Eliminate all members of C whose affinity with the antigen is less than a pre-defined threshold (ct)
8 Determine the affinity amongst all the antibodies in C and eliminate those antibodies whose affinity with each other is less than a pre-specified threshold (ct)
9 Incorporate the remaining clones in C into N
10 end
11 Determine the affinity between each pair of antibodies in N and eliminate all antibodies whose affinity is less than a pre-specified threshold nt
12Introduce a number (a) of new randomly generated antibodies into N
13 until a stopping condition has been met

- Danger Theory inspired method

This theory is tried to describe the nature as well as functioning of an immune output or response in different course of action with respect to own or self versus non self point. It tells that human being immune system or structure can find out dangerous in counting to antigens to activate appropriate immune system output or responses.

- Dendritic Cell Technique (DCA):

DCA was proposed by Greensmith et al., (2005) which tell the sign of hazardous signals, sheltered signals and data signal at any specific time. Dendritic cells abbreviated as DCs are part of mammalian immune system called as immune cells. It is used in order to process antigen material s well as exist it on the surface to immune system other cells.

Algorithm 21: DCA Algorithm:
input: S = set of data items to be labelled safe or dangerous
output: L = set of data items labelled safe or dangerous
1 Create an initial population of dendritic cells (DCs), D
2 Create a set to contain migrated DCs, M
3 forall the Data items in S do
4 Create a set of DCs randomly sampled from D. P

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5 forall the DCs in P do
6 Add data items to DCs' collected list
7 Update danger, PAMP and safe signal concentrations
8 Update concentrations of output cytokines
9 Migrate dendritic cell from D to M and create a new DC in D if concentration of costimulatory molecules is above a threshold
10 end
11 end
12 forall the DCs in M do
13 Set DC to be semi-mature if output concentration of semi-mature cytokines is greater than mature cytokines, otherwiseset as mature
14 end
15forall the Data items in S do
16Calculate number of times data item is presented by a mature DC and a semi-mature DC
17 Label data item as safe if presented by more semi-mature DCs than mature DCs, otherwise label it as dangerous
18 Add data item to labelled set M
19 end

- Biogeography based / dependent optimization (BBO):

BBO was explored by Simon, (2008). It was opted by the thesis of island biogeography equilibrium. It states that rate of variation of the counting of species exist on island based critically upon the balancing among immigration of newly generated ones onto the land, also the emigration or moving overseas of traditional species.

Algorithm 22: BBO Algorithm

1 Initialize a set of solutions (habitats) to a problem
2 while termination condition not met do
3 Evaluate the fitness (HSI) for each solution
4 Compute S, λ and μ for each solution
5 Modify habitats (Migration) based on λ and μ
6 Mutation based on probability
7 Implement elitism to retain the best solutions in the population from one generation to the next.
8 end

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In this algorithm, each one is having its own rate of immigration as well as emigration. As large number species are inhabit the island, then rate of immigration decreases also the emigration rate enhance. In this technique, the solution which is good is ready to share their features with solution which is poor.

8. Application of meta-heuristics

Applications of meta-heuristics techniques falls into following area namely,

- Engineering design, geopolitical optimization, structural optimization for electronics,
- Aerodynamics, dynamics of fluid, communications, automation, VLSI area
- Machine learning area, data mining, computational biology
- Economics as well as finance, In Computer networks, security
- System modeling, virtual running or simulation
- In chemical, physic cal, biological aspects
- Control engineering, signal as well as image processing

FUTURE RESEARCH DIRECTIONS

Research gaps and future work despite success of meta-heuristic methods on diversified areas of science, engineering and technology, there remains sufficient gap that needs to be filled in order to reach maturity level as compared to other established fields of research. This section helps identify some of the related but potential areas of research that may build future literature. Mathematical analysis of rate of convergence and efficiency help obtain in-depth information about the behavior of an algorithm on a specific problem. This will help effectively modify existing or develop new method with authentic (not ad-hoc) results. Few efforts can be witnessed in literature trying to address this gap, however to reach maturity in this area, meta-heuristic researchers need a lot of work in future. Another open area in meta-heuristic research identified by this work is measuring the balance between exploration and exploitation. On part of comparative performance measurement, the study urges any agreed criteria instead of just comparing objective function values and number of function evaluations. These algorithms will be smart

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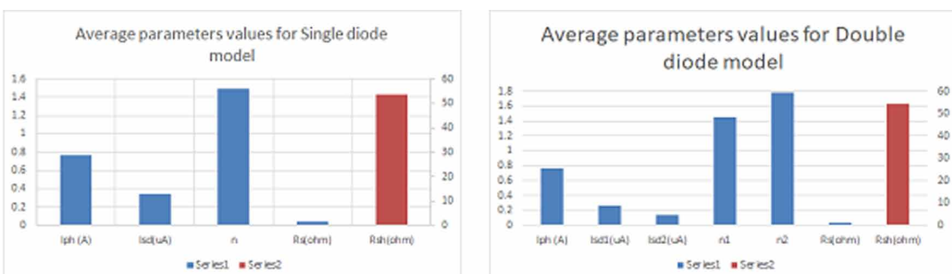
enough to tune their parameters in order to find optimum quality solution with minimum computational cost. Researcher also predicts the next eight to ten years to be significant in addressing this open problem residing both in theory and practice. A promising but not fully explored direction is to combine exact algorithms and meta-heuristics to solve optimization problems.

ANALYSIS OF VARIOUS METHA-HEURISTIC METHODS

In this book chapter meta-heuristic based techniques are described in details for solving various optimization problems. For high efficiency solar cells as the number of carriers increase with the applied voltage, the recombination at the rear surface changes dramatically with voltage. In such cases the analysis is best performed by a single diode, but allowing both the ideality factor and the saturation current to vary with voltage. In such cases, which are quite common in silicon devices, a double diode fit yields erroneous values.

Figure 5. a) Average parameters values for SDM, b) Average parameters values for DDM



In Single diode model I_{ph}, I_{sd}, n, R_s, R_{sh} values are considered whereas in double diode model I_{ph}, I_{sd1}, I_{sd2}, n_1, n_2, R_s, R_{sh} values are considered. By seeing the values of various parameters, I_{ph} & R_{sh} values are almost same with respect to single and double diode model even though internal circuit diagram of both the models are different. By seeing the other parameters values from the graph, we can conclude that double diode model shows the improvement. In literature also two diode models is recommended for improved accuracy but increased circuit complexity. For these analysis various algorithms namely SA,

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CPSO, Rcr-IJADE, GOTLBO, CSO, BFA, PS, NEWTON, ABC, PSO, GA, HS, GGHS, IGHS, DE, LMSA, ABSO, NM- MPSO, BMO, IADE, M-ABC, NOVEL BMO, CARO, WOA, IWOA, BPFPA, FPA etc. are considered for single diode model. For double diode model various algorithms namely, CWOA, BMO, STBLO, PS, HS, GGHS, IGHS, ABSO, SA, Rcr-IJADE, CSO, GOTLBO, BFA, ABC, PSO, GA, HYBRID-PSO, NM-PSO, M-ABC, BBO-M, SATLBO, CARO, IJAYA, MSSO, WOA, IOWA, FPA, BPFPA, BBO etc. are considered.

In single diode model graph five parameters are considered with various ranges. It is observed in figure 5, for parameter I_{ph}, minimum value is 0.76 for BPFPA algorithm and maximum value is 0.76979 for CARO algorithm. Minimum I_{sd} value is 0.3049 for HS and maximum value is 0.4798 for SA algorithm. HS method represents 1.4753 minimum n value and 1.6 maximum n value for PS method. Maximum series resistance obtained is 0.0366 for BPFPA whereas minimum value is 0.0299 for GA method. Shunt resistance value range is 50.8691 for BFA to 59.012 for algorithm. For Iph parameter, NOVEL-BMO algorithm is showing out of range value which is not coinciding with other algorithms values in literature. Similarly BFA, PS, GA, NOVEL-BMO algorithms are giving out of range values for Isd parameter. For n value two algorithms namely BFA and NOVEL-BMO showing outside range values. For R_s parameter, NOVEL-BMO algorithm is showing out of range value which is not coinciding with other algorithms values. SA, CPSO, PS, GA, NOVEL-BMO, WOA, BPFPA algorithms will shows the improper value range for shunt resistance with respect to single diode model.

For double diode model seven parameters are considered. It is observed in figure 6, I_{ph} shown 0.7594 minimum value for BBO and 0.7623 maximum value for SA algorithm. It is found that min I_{sd1} value is 0.1905 for WOA method and max value is 0.37014 for GGHS method whereas I_{sd2} is minimum for PSO which is 0.01 and maximum for ABSO algorithm which is 0.38191. Minimum n_1 value is found to be 1.2186 for IJAYA and n_2 minimum is 1.42309 for BBO method. It can be observed that maximum n_1 value is 1.5172 for SA algorithms and maximum n_2 value is 2 for STLBO algorithm. Series resistance should be as small as possible. In graph is observed that 0.032 minimum value is for PS technique whereas maximum value is 0.0376 for IJAYA technique. Minimum shunt resistance is 43.1034 is for SA and maximum is 60 for BFA. For Iph parameter, Rcr-IJADE algorithm is showing out of range value which is not coinciding with other algorithms values in literature. Similarly PS, HS, IGHS, SA, GOTLBO, BFA,ABC, PSO GA, M-ABC,BMO-M, IJAYA, IWOA algorithms are giving out of range values

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for I_{sd1} parameter whereas CWOA,BMO, PS, CSO, GA, H-PSO, NM-PSO, SLTLBO. IJAYA, MSSO algorithms are giving out of range values for I_{sd2} parameter. For n_1 value PS, IGHS, M-ABC, BBO-M, IWOA, BBO, DE methods are not showing proper results. PS method gives out of range n_2 value. STBLO, Rcr-IJADE, GOTLBO methods are showing comparatively large series resistance whereas PS, GGHS, IJAYA gives comparatively low shunt resistance value.

CONCLUSION

The development of PV system raised the need of PV system. Meta-heuristics are widely recognized as efficient approaches for many optimization problems. In this chapter, various meta-heuristic optimization methods have been discussed and analysis is done to evaluate the impact of model parameters on the operation of PV cell. The PV models discussed here are single-diode model, the two-diode model. This paper provides a survey of different meta-heuristics techniques. It outlines the components and fundamentals that are used in various meta-heuristics in order to analyze their concepts. The literature survey is accompanied by the presentation of references for further details, including applications. This work surveyed several important meta-heuristic methods as they are described in the literature by considering its classification. Despite the lack of theoretical foundation, the advantages of meta-heuristics are widely reported in the literature. The assessment of meta-heuristics is commonly based on experimental comparisons.

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Chapter 2
Comparative Analysis of Advanced Controllers for Standalone WECs for DC Microgrid Applications

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ABSTRACT

The small-scale wind energy generation system is one of the solutions to empower the isolated loads and provides a promising solution to decrease the greenhouse effect. This chapter describes the simulation analysis for wind energy conversion system incorporated with maximum power point tracking feature. The MPPT algorithms like variable current perturb and observe algorithm and variable step perturb and observe algorithm are incorporated with WECS. The comparative analysis is done in the closed-loop model in continuous time-varying wind speed. The closed-loop simulation is performed using a conventional fixed gain controller. To address the limitations of the fixed gain controller, the analysis is done using the gain scheduling proportional integral controller and the good gain method to tune the proportional integral controller. The comparative analysis between the fixed gain controller, the gain scheduling proportional integral controller, and the good gain method to tune proportional integral controller for above-stated MPPT methods is shown.

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INTRODUCTION

Recently, the load demand for renewable energy has been boosted by the increase of the price of conventional fuels and limited reserve capacity available for the foreseeable future. The present and future energy crisis and depleting nature of conventional sources have led to an increased interest in power generation through non-conventional sources of energy. Renewable is the fastest-growing source of energy for electricity generation, with an average increase of 2.9% per year from 2012 to 2040. Now, renewable resources have become vital elements for electrification, and some of the primary sources renewable are wind, solar, tidal, biomass, etc. Among all renewable sources, wind energy is gaining more support due to its zero-carbon emission and its cost-effectiveness, and it is the most rapidly growing means of distributed power generation. (Powersim, Inc, 2021)

Up to now, most of the wind energy generation systems have been implemented in large-scale projects at the megawatt level. However, small-scale WECS can provide a good alternative in urban areas and residential applications in remote places where connection to the grid is almost impossible. Wind energy is the most rapidly growing technology for renewable power generation in the world. The large increasing electrical penetration of large wind turbines into electrical power systems is inspiring continuously the designers to develop both custom generators and power electronics, and to implement modern control system strategies. The continued growth and expansion of the wind power industry in the face of a global recession and a financial crisis is a testament to the inherent attractiveness of the technology. Wind power is clean, reliable, and quick to install; it's the leading electricity generation technology in the fight against climate change, enhancing energy security, stabilizing electricity prices, cleaning up our air, and creating thousands of quality jobs in the manufacturing sector when they're particularly hard to come by. (Powermin, n.d.) India ranks 4th in over global market of wind energy and there are many number of installations are there for India in 2010. The highest totals were Germany, Spain, the USA, India, and Demark.

The various types of material are used for manufacturing of blades for the wind turbine proposed in (Mishnaevsky et al., 2017) discussed about different types of materials for wind turbine blades. A technical overview of WECS have been discussed in paper (Babu & Arulmozhivarman, 2013). The author proposed novel P&O (NPO)MPPT technique with incorporation of PMSG and boost converter for WES (Dalala, Zahid, Yu et al, 2013). Authors have

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used the concept of detection of wind speed in indirect way by observing the slope of the DC link voltage across DC load. The DC current as a perturbing variable is used in this paper. They have tested the system under sudden change in wind speed and gradual change in wind speed. The authors proposed overall control strategy for small scale wind energy system with stall control feature in (Dalala, Zahid, & Lai, 2013). At high wind speed wind turbine will stall. The algorithm works on constant power stall and constant speed stall. The power coefficient is one of the most important and crucial factor in the WES, as it decides the conversion efficiency of wind turbine. Power coefficient analysis based MPPT is proposed in (Xia et al., 2011). Authors in (Ramadan, 2019) proposed variable-step perturb and observe algorithm(VSPO) for large grid integrated wind turbine generation system using model predictive control. They have proposed system efficiency enhancement by proposing method compared to conventional method. They have also considered the random change in wind profile to justify the results of proposed algorithm. In paper (Joshi & Pandya, 2013; Joshi et al., 2018; Panda et al., 1997; Pandya et al., 2021) Gain scheduling PI techniques have been proposed by the authors. Modeling and design of WECS and its parameters have been discussed in (Arnest & Wizelius, 2011; Burton, 2011; Control, ; Green, 2012; Kundur, 1994; Lara, 2009; Masters, n.d.; Rause, 2002; Sumathi et al., 2015). For extraction of maximum power from the wind maximum power point tracking is used, author in (Bakhtiari & Nazarzadeh, 2020; Haq et al., 2020; Li et al., 2019; Tazay et al., 2020) discussed about various types of maximum power point tracking systems for wind and hybrid systems of renewable energy sources.

The sector-wise Renewable Energy Cumulative Achievements for grid-interactive power is shown in Table 1 and 2. (MNRE).

Table 1. Indian power sector scenario as of January 2020. (MNRE)

Sector	Generation in MW
Small Hydro power	4758.455
Wind power	38683.65
Bio Power Total	10314.56
Ground mounted solar PV	34561.33
Rooftop solar PV	4232.74

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Table 2. Contribution of the renewable power sector in Indian power sector as of January 2020. (MNRE)

Sector	Generation in MW
Wind	38433.55
Bio Mass	937387
Small hydro	4740.47
Solar	33508.31

This work basically focuses on the MPPT algorithms for WECS. The incorporation of MPPT algorithm extracts maximum power from the moving air i.e. wind. The comparative analysis for variable current P & O algorithm and variable step P & O algorithm has done with incorporation of PI controller. To address the limitations of the PI controller the simulation analysis with Gain scheduled PI controller and good gain methods are introduced. The first portion focuses on introductory remarks, literature review and flow of the paper. The second portion focuses on the mathematical model of WECS. The third portion describes about the wind turbine modelling with threshold limits. The fourth segment demonstrates description of MPPT method. The fifth portion of the work demonstrates the modelling of advanced controller with their characteristics equations. The sixth segment demonstrates the comparative analysis of various advanced controllers implements for WECS with incorporation of MPPT.

MATHEMATICAL MODELING OF WECS

Basically, the Wind energy conversion system is made up of a Wind source, Wind turbine, Generator, Boost converter, and load. So for doing system modeling we have to model each and every component of a particular standalone wind energy conversion system. In this chapter, we will discuss the mathematical modeling of Wind turbine, PMSG generator, and mathematical modeling of boost converter respectively.

Modeling of Wind Turbine

For modeling a wind turbine, we have to consider the turbine, wind source, gearbox, and generator.

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First for the wind source,

The Kinetic energy is given by,

$$E = \frac{1}{2} m V^2 \tag{1}$$

But for the power, if the wind

$$P_v = \frac{1}{2} \rho A V^3 \tag{2}$$

Where A is the surface area at which wind is applied for a generation.

The turbine torque T_t is denoted by,

$$T_{wt}(t) = T_e(t) + J_{eq} \frac{d\omega_m}{dt}(t) + F\omega_m(t) \tag{3}$$

Where J_{eq} is the equivalent inertia and F is friction.

The power of the turbine is $P_t = C_p * P_V$

Where the C_p is the power coefficient.

C_p is mainly dependent upon the λ (Tip Speed Ratio) and β (Blade Pitch angle)

Therefore C_p (λ,β) = Power coefficient

$$C_P = 0.22(\frac{116}{\beta} - 0.4\theta - 5)e^{\frac{-12.5}{\beta}} \tag{4}$$

Where $\beta = \cfrac{1}{\cfrac{1}{\lambda + 0.08\theta} - \cfrac{0.035}{\theta^3 + 1}}$

The total torque is $T(t) = T_{wt}(t) - T_e(t)$

$$T(t) = J_{eq} \frac{d\omega_m}{dt}(t) + F\omega_m(t) \tag{5}$$

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Modeling of PMSG

To extract wind power, permanent magnet-type machines are used in recent days because of the numerous advantages of PM-type machines. The main advantages of PMSG types of machines are self-excitation, direct drive, it has better thermal characteristics, etc. As compared to other generators, the PMSG has the advantage of being directly coupled to a wind turbine with an absence of a gearbox; there is no need for excitation current as in the doubly-fed induction generator (DFIG.) case, and there is no direct connection between the generator and the grid for grid-tie applications. PMSG is the best option for small-scale WECS.

The dynamic model of the PMSG is obtained from two synchronous reference frames which are the q axis 90 degrees ahead of the d axis with respect to the direction of the rotation. (Kundur, 1994)

Some assumptions for the derivation are,

- The MMF in the air gap is distributed sinusoidal and the harmonics are neglected.
- Saliency is restricted to the rotor. The effect of slots in the stator is neglected.
- Magnetic saturation and hysteresis are ignored.

Equations for the d and q axis of the synchronous machine is written as

$$V_d(t) = R_s i_d(t) + L\frac{di_d}{dt}(t) - e_q(t) \tag{6}$$

$$V_q(t) = R_s i_q(t) + L\frac{di_q}{dt}(t) - e_d(t) \tag{7}$$

Where e_d & e_q are the total dq back emf components

$e_d(t) = \omega_e(t)[Li_d + \psi_m]$

$e_q(t) = \omega_e(t)Li_q(t)$

Where ω_e is angular speed which can be found pole pair (p) and rotor speed (ω_m)

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Transfer Function of Boost Converter

The boost converter converts the rectified DC voltage into a DC voltage of the desired magnitude. The boost converter operates in the continuous conduction mode. In mode 1, the switch is ON, the diode is in the OFF condition, and the inductor stores energy. During this period, the capacitor supplies the output current. In mode 2, the switch is in the OFF condition, the capacitor stores energy, and the energy stored in the inductor gets dissipated.

There are two modes of operations (dT_s & (1-d) Ts).

For dTs

$$\begin{bmatrix} \dot{i}_L \\ \dot{V}_c \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{RC} \end{bmatrix} * \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} * \begin{bmatrix} V_g \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{C} \end{bmatrix} * \begin{bmatrix} i_z \end{bmatrix} \tag{8}$$

For (1-d) Ts,

$$\begin{bmatrix} \dot{i}_L \\ \dot{V}_c \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} * \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} * \begin{bmatrix} V_g \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{-1}{C} \end{bmatrix} * \begin{bmatrix} i_z \end{bmatrix} \tag{9}$$

Output equation will be

$$\begin{bmatrix} \dot{V}_0 \\ \dot{i}_g \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} * \begin{bmatrix} i_L \\ V_c \end{bmatrix} \tag{10}$$

Now the small-signal model for the boost converter is written as,

$$\begin{bmatrix} \dot{\hat{I}}_L \\ \dot{\hat{V}}_c \end{bmatrix} = \begin{bmatrix} 0 & \frac{-(1-D)}{L} \\ \frac{(1-D)}{C} & \frac{-1}{RC} \end{bmatrix} * \begin{bmatrix} \hat{I}_L \\ \hat{V}_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 & \frac{V_C}{C} \\ 0 & \frac{-1}{C} & \frac{-I_C}{C} \end{bmatrix} \begin{bmatrix} \hat{V}_g \\ \hat{I}_L \\ \hat{d} \end{bmatrix} \tag{11}$$

And the output equation for the small-signal model is,

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$$\begin{bmatrix} \hat{V}_0 \\ \hat{I}_g \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} * \begin{bmatrix} \hat{I}_L \\ \hat{V}_c \end{bmatrix} \tag{12}$$

The state-space transfer function is,

$$A = \begin{bmatrix} 0 & \frac{-(1-D)}{L} \\ \frac{(1-D)}{C} & \frac{-1}{RC} \end{bmatrix}, \ B = \begin{bmatrix} \frac{1}{L} & 0 & \frac{V_C}{C} \\ 0 & \frac{-1}{C} & \frac{-I_C}{C} \end{bmatrix}, \ C = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

SYSTEM DESCIRPTION OF STAND-ALONE WIND ENERGY CONVERSION SYSTEM

The wind is a free, clean, and inexhaustible type of solar-powered energy. Winds originate from the uneven heating in the atmosphere from the sun, the irregularities from the earth's surface, and the rotation of the earth. Wind flow patterns are modified through the land terrain, environmental conditions, and buildings. This wind flow, or motion energy, when harvested by modern wind turbines, enables the generation of electricity. The terms wind energy or wind generation describes the task where the wind is utilized to come up with mechanical power or electricity. (Masters, n.d.)

In the small scale WECS the turbine is directly connected with PMSG. The load is interfaced with an uncontrolled rectifier (diode bridge rectifier) and PWM-based DC-DC converter. The switch S of the converter operates with the MPPT controller and as per the change in duty cycle, the voltage across the load will boost. The load resistor will replace by connecting the inverter to the fed AC load. This configuration is shown in Figure 1. (Dalala, Zahid, Yu et al, 2013)

The general modeling equations of gross mechanical power and net power with conversion efficiency can be expressed as below,

Conversion efficiency can be expressed as (13),

$$Pmech = \frac{1}{2}\rho A V^3 \tag{13}$$

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Power captured by the blades of a wind turbine is,

$$Pnet = \frac{1}{2}\rho A C_p(\lambda, \beta)V^3 \quad (14)$$

The Tip speed ratio of the wind turbine can model as per equation (15),

$$TSR = \frac{\omega R}{V} \quad (15)$$

The equation of torque is modeled in eq. (16),

$$Turbine = \frac{1}{2}\rho A C_p \frac{V}{\lambda} \quad (16)$$

Where, Pmech = Mechanical power from a wind turbine in Watt, Pnet = Net power from wind turbine after Betz limit and multiplication of power coefficient, r = Air density (1.225kg/m^3), A = Swept area of the wind turbine in m^2, C_P = Power coefficient of the wind turbine, v = Velocity of wind or wind speed in m/s, l = Tip speed ratio of the wind turbine, b = Blade pitch angle.

BETZ's Limit for Wind Turbine

Wind turbines follow the Betz law and according to that entire system will work. No wind turbine could convert more than 59.2% of the kinetic energy of the wind into mechanical energy turning a rotor. This is known as the Betz Limit and is the theoretical maximum coefficient of power for any wind turbine. For good turbines, Betz limit is within the range of 35-45%. (Dalala, Zahid, & Lai, 2013; Dalala, Zahid, Yu et al, 2013; Masters, n.d.; Xia et al., 2011)

MPPT ALGORITHMS FOR STANDALONE WECS

To get a clear idea about the working of standalone WECS and MPPT control strategy, we have simulated the system for two different MPPT algorithms Proposed in (Dalala, Zahid, & Lai, 2013; Dalala, Zahid, Yu et al, 2013).

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Variable Current P&O (Electrical P&O) Algorithm

The first MPPT generates the reference current from the MPPT algorithm which is compared with the actual current, however, by observing the variation in the voltage at the load side with the change in wind speed has been observed. Based on the wind conditions, the algorithm works on one of two modes of operation: normal P&O mode under slow varying wind speed conditions. In this mode, the algorithm finely tunes to the MPP as long as the wind speed is slowly varying or steady. The MPPT technique comprises of the voltage sensor and current sensors which takes voltage and current sample to send the signal to the MPPT controller. The MPPT controller generates a reference current which then generates a suitable gate pulse to drive the power MOSFET. The control diagram which is interfaced with the power circuit is shown in Figure 1.

Variable Step P&O (Mechanical P&O) Algorithm

The other MPPT technique comprises of the sensing of the mechanical parameters, the perturbation has been observed in angular speed w and shaft power P_0. The generation of variable step size is computed by detecting the difference between the actual value of the rotor speed and the optimal value of the rotor speed. The developed algorithm which is coded is a simplified C block splits the P–ω characteristic curve of WT into modular sectors and determines the perturbation step size by comparing a suggested ratio, which depends on the optimal rotor speed with a specified ratio which is specified according to the required power accuracy. The rectified voltage, shaft power, and wind speed have been sensed and they have been treated as input parameters of the code. The power is extracted as an output which is then compared with the shaft power. The comparison of these two powers will decide the duty cycle of the boost converter. With the incorporation of the PI controller, the PWM signals are generated. The control diagram of this MPPT method with a power circuit is shown in Figure 2. (Ramadan, 2019)

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MODELING OF FIXED GAIN CONTROLLER AND ADVANCED CONTROLLERS

Fixed Gain Controller (Convectional PI Controller)

Proportional Integral (***PI***) ***control*** is a common variant of ***PID control*** that does not have a derivative term; A P.I Controller is a feedback control loop that calculates an error signal by taking the difference between the outputs of a system. The parallel form of a PID controller has a transfer function: (Circuit et al., 2001; Mahdi et al., 2011)

$$C(s)= K_p+\frac{Ki}{s}+K_d s \tag{17}$$

Where: K_p: = Proportional Gain, K_i: = Integral Gain, K_d: =Derivative gain

From equation 17 and various combinations of parameters of PID controller, we can design different types (P, PI, PID controllers) as per our requirements.

We want PI configuration so we consider $K_p{}^{1}0$, $K_i{}^{1}0$ and $K_d=0$

From eq (17)

$$C(s) = K_p+\frac{Ki}{s} \tag{18}$$

Implementation of both MPPT algorithms for the fixed gain PI is shown in figures 3(a) and 3(b) respectively. Figure 3(a) shows the fixed gain PI controller implemented with variable current P&O algorithm and Figure 3(b) shows the fixed gain PI controller with variable step P&O algorithm.

Gain Scheduling PI Controller

The fixed gain controller has the demerits of a higher probability of failure at a high level of uncertainty, failure to operate in desired fashion under the change in input conditions, need for retuning of gains. Zeigler Nicolas's method can help in the determination of controller gains, but it is an offline tuning method. Moreover, this method has the drawbacks of little usage of

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process information in design criteria leading to poor robustness. On the other hand, gain scheduling can be an alternative due to its ability to track the rapid changes in the operating conditions. (Joshi et al., 2018; Panda et al., 1997)

Figure 4 shows the block diagram for the GSPI controller implemented for the control of the primary and auxiliary source. The output of GSPI, u_{dc} (t), can be mathematically deified as:

$$u_{dc}(t) = K_p * e(t) + K_i \int_0^t e(\tau) d\tau \tag{19}$$

Where e (t) is the sensed or actual value of voltage/current, Kp (t) and K_i(t) is the instantaneous values of proportional and integral gains, and t is time. Kp (t) can be represented as a function of the input error signal e (t) as in Eq. (19), where a is a constant, and Kp_{max} and Kp_{min} are the maximum and the minimum values of Kp. When e (t) is large, the exponential term approaches zero; therefore, K_p (t) = K_{pmax}. Similarly, when e (t) is small, the exponential term approaches unity. This results in K_p (t) = K_{pmin}. This implies that the larger the e (t), the larger the K_p will be, resulting in a fast response during the transient period. To avoid the undesirable problems of overshoot, the gain scheduling algorithm ensures that K_p (t) is small when e (t) is small. Hence, K_p (t) = K_{pmin}. The constant 'a' in (19) determines the rate of variation of the proportional gain for the transient conditions, the large proportional gain is employed to drive the large error towards zero and thereby drive the process toward the steady-state condition. (Joshi et al., 2018)

$$K_p(t) = K_{P(\max)} - (K_{p(\max)} - K_{p(\min)})e^{-(a|e(t)|)} \tag{20}$$

Integral gain, K_i (t), in Eq. (20) as a function of the error signal e (t) can be expressed as,

$$K_i(t) = K_{i(\max)} e^{-(a\lfloor e(t) \rfloor} \tag{21}$$

Where g is a constant and K_i (max) is the maximum value of integral gain. The value of g varies between 0 and 1 depending upon e (t). If e (t) is small, K_i (t) needs to be large so as to drive the steady-state error to zero. (Panda et al., 1997)

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GSPI offers the advantage of a variation of K_p and K_i as a function of error input. The performance of GSPI controllers does not suffer from performance degradation under the system disturbances and parameter variations. This results in improved controller performance under dynamic and steady-state conditions. The only demerit is the need for additional computations for the determination of K_p and K_i at every iteration. (Joshi et al., 2018; Panda et al., 1997)

Implimentation of both MPPT algorithms for the GSPI is shown in figures 5(a) and 5(b) respectively. Figure 5(b) shows the GSPI controller impelimented with variable current P&O algorithn and Figure 5(b) shows the GSPI controller with variable step P&O algorithm.

The Good Gain Method

The Good Gain method is a simple, experimental method that can be used on a real process (without any knowledge about the process to be controlled), or simulated system (in this case you need a mathematical model of the process, of course), see Figure 6. (Haugen, 2010)

The Good Gain method aims at giving the control loop better stability than the famous Ziegler-Nichols' methods, the Closed-loop method, and the Open-loop method gives. The Ziegler-Nichols' methods are designed to give an amplitude ratio between subsequent oscillations after a step change of the set point equal to 1/4 ("one-quarter decay ratio"). This is often regarded as poor stability. The Good Gain method gives better stability. Furthermore, the Good Gain method does not require the control loop to get into oscillations during the tuning, which is another benefit compared with the Ziegler-Nichols 'methods. (Haugen, 2010)

Tuning Procedure

1. The procedure described below assumes a PI controller, which is the most commonly used controller function. However, a comment about how to include the D-term, so that the controller becomes a PID controller, is also given in (Haugen, 2010). Bring the process to or close to the normal or specified operation point by adjusting the nominal control signal u0 (with the controller in manual mode).
2. Ensure that the controller is a P controller with $K_p = 0$ (set T_i = ¥ and T_d = 0). Increase K_p until the control loop gets good (satisfactory) stability

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as seen in the response in the measurement signal after e.g. a step in the set point or in the disturbance (exciting with a step in the disturbance may be impossible on a real system, but it is possible in a simulator). If you do not want to start with $K_p = 0$, you can try $K_p = 1$ (which is a good initial guess in many cases) and then increase or decrease the K_p value until you observe some overshoot and a barely observable undershoot (or vice versa if you apply a set point step change the opposite way, i.e. a negative step change), If such limits are reached the K_p value may not be a good one probably too large to provide good stability when the control system is in normal operation. So, you should apply a relatively small step change of the set point (e.g. 5% of the set point range), but not so small that the response drowns in noise. (Haugen, 2010)

3. Set the integral time T_i equal to

$$T_i = 1.5 * T_{ou} \tag{22}$$

where T_{ou} is the time between the overshoot and the undershoot of the step response (a step in the set point) with the P controller. (Haugen, 2010)

Since the good gain PI controller cannot predict the future errors of the system it cannot decrease the rise time and eliminate the oscillations.

COMPARITIVE ANALYSIS OF FIXED GAIN AND ADVANCED CONTROLLERS FOR MPPT ALGORITHMS

This section comprises of the comparative analysis of the Fixed gain, the GSPI, and the Good gain PI controller. This section compares all three controllers for the variable current P&O algorithm and variable step P&O algorithm with a small-scale wind energy conversion system discussed above. The system is tested for steady-state as well transient conditions.

For both algorithms VCPO and VSPO we have applied the following cases:

1. Analysis for Fixed wind speed 7m/s for constant loading condition at 15 Ω
2. Analysis for Fixed wind speed 7m/s for constant loading condition at 20 Ω

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3. Analysis for Fixed wind speed 7m/s for constant loading condition at 25 Ω
4. Analysis for Fixed wind speed 7m/s for constant loading condition at 27 Ω
5. Analysis for variable wind speed at constant loading condition 27 Ω
6. Analysis for variable wind speed with variable loading conditions.
7. Analysis for fractional wind speed.

For above mentioned cases, we have plotted output power, output voltage, and output current results and compare them with all the above mentioned cases. We have taken a change in load resistance as a change in loading conditions because our system is standalone WECS and DC link voltage is measure across the resistive load. Change in wind speed is given at the input end.

Simulation Results for Variable Current P&O MPPT Method

This section represents the incorporation of the variable current P&O algorithm for small-scale wind energy conversion systems. WECS is Simulated in PSIM for various permutation and combinations for fixed gain (CPI), GSPI, and good gain PI controllers as shown in Figure. 3(a), 5(a), and 7(a) respectively, and analysis is done based on output power, DC link voltage and output current for fixed gain and advanced controllers.

Analysis for Fixed Wind Speed 7m/s for Constant Loading Condition at 15 Ω with Variable Current P&O Algorithm (Electrical P&O)

This case presents the Small scale WECS with variable current P&O algorithm for Fixed gain, GSPI, and good gain PI controllers tested for the fixed wind speed 7m/s and loading condition at 15 Ω.

The Figure. 8 presents the results of output power, voltage, and current for Fixed gain (CPI), GSPI, and GG. For the 3kW stand-alone WECS with variable current P&O algorithm fixed gain PI controller is giving 2484.6W output power, GSPI is giving 2442.6W and the good gain PI controller is showing 2677.0W for fixed wind speed 7 m/s and loading condition 15 Ω.

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Table 3 represents the various quantities of the WECS for fixed wind speed for the fixed gain PI, the GSPI, and the GG PI controllers.

Table 3. Response for Fixed wind speed 7m/s for constant loading condition at 15 Ω with variable current P&O algorithm

PI controlling technique	Voltage from generator (RMS) in V	Current from generator (RMS) in A	Voltage after rectification in V	Voltage after boost in V	Power drawn in W	Output voltage in V	Load Resistance in Ω
Fixed gain PI	56.9	27.2	74.3	193.1	2484.6	193.1	15
GSPI	53.7	32.4	65.8	187.4	2442.6	187.4	
Good Gain PI	59.0	28.3	77.2	200.4	2677.0	200.4	

Analysis for Fixed Wind Speed 7m/S for Constant Loading Condition at 20 Ω with Variable Current P&O Algorithm (Electrical P&O)

Likewise, for this case, wind speed is still kept constant at 7 m/s loadings is changes to 20 Ω for all three controllers with the variable current P&O algorithm for stand-alone WECS.

For constant wind speed of 7m/s and loading condition for 20 Ω from table 4 the response of all three controllers is visible. Fixed gain PI providing 2332.9W, GSPI providing 2446.8W, and GG providing 2522.6W. In Figure. 9 the results for DC link voltage and current for three controllers are shown.

Table 4. Response for Fixed wind speed 7m/s for constant loading condition at 20 Ω with variable current P&O algorithm

PI controlling technique	Voltage from generator (RMS) in V	Current from generator (RMS) in A	Voltage after rectification in V	Voltage after boost in V	Power drawn in W	Output voltage in V	Load Resistance in Ω
Fixed gain PI	58.2	25.2	76.1	216.0	2332.9	216.0	20
GSPI	54.0	32.2	66.7	217.2	2446.8	217.2	
Good Gain PI	60.5	26.1	79.3	224.6	2522.6	224.6	

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Analysis for Fixed Wind Speed 7m/s for Constant Loading Condition at 25 Ω with Variable Current P&O Algorithm (Electrical P&O)

Table 5. Response for Fixed wind speed 7m/s for constant loading condition at 25 Ω with variable current P&O algorithm

PI controlling technique	Voltage from generator (RMS) in V	Current from generator (RMS) in A	Voltage after rectification in V	Voltage after boost in V	Power drawn in W	Output voltage in V	Load Resistance in Ω
Fixed gain PI	59.0	23.7	77.4	235.8	2224.4	235.8	25
GSPI	54.2	32.4	66.6	239.9	2390.3	239.9	
Good Gain PI	61.5	24.6	80.7	245.6	2411.8	245.6	

Similarly, as in the above mentioned case, we change the loading conditions from 20 Ω to 25 Ω for CPI, GSPI, and GG controllers.

For load resistance 25 Ω the output power is increase for the fixed wind speed 7m/s for the same small-scale WECS implemented with variable current P&O algorithm. For this case where the wind speed is fixed and load is constant fixed gain PI controller shows 2224.4W, GSPI shows 2390.3W and 2411.8W output power. All other responses of voltage and current are tabulated in table 5.

Analysis for Fixed Wind Speed 7m/s for Constant Loading Condition at 27 Ω with Variable Current P&O Algorithm (Electrical P&O)

The variable current P&O algorithm is implemented with Fixed Gain and advanced controllers like GSPI and Good gain PI controllers are tested for fixed wind speed 7 m/s and loading at 27 Ω in small scale WECS.

This analysis demonstrates four cases for VCPO MPPT algorithm implemented for 3kW WECS. The analysis is done for permutations and combinations of wind speed and load. Sections 6.1.1-6.1.4 indicates the simulation results for the fixed wind speed 7m/s for the constant loading conditions like 15Ω, 20Ω, 25Ω, and 27Ω for The fixed gain PI, the GSPI, and the good gain PI controllers. The simulation results are taken based on

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various parameters of WECS like output power, DC link voltage and output current. Various quantities of the WECS is taken into consideration in the tabular format. From the critical analysis it is shows that for the steady state conditions VCPO algorithm showing effective results. The adaptive techniques address the limitations of the fixed gain PI controllers.

Table 6. Response for fixed wind speed 7m/s for constant loading condition at 27 Ω with variable current P&O algorithm

PI controlling technique	Voltage from generator (RMS) in V	Current from generator (RMS) in A	Voltage after rectification in V	Voltage after boost in V	Power drawn in W	Output voltage in V	Load Resistance in Ω
Fixed gain PI	59.4	23.1	78.0	242.3	2175.1	242.3	27
GSPI	54.1	32.6	66.6	249.2	2388.9	249.2	
Good Gain PI	61.9	24.0	81.3	252.5	2306.7	252.5	

Analysis for Variable Wind Speed at Constant Loading Condition 27 Ω

The wind is changing every time. So for change in wind speed system should be tested. Therefore, we have applied a change in wind speed for fixed loading condition 27 Ω for all three types of controllers CPI, GG, and GSPI.

Table 7. Response for variable wind speed at constant loading condition 27 Ω

Wind speed in m/s	6	6	7	7	8	8	6	6
Time	0	0.5	1.5	2.5	3.5	4	5	6

This analysis represents the variable change in wind speed for constant loading condition for small scale WECS. The wind speed for first 0.5 second is at 6 m/s and till 2.5 second it is of 7 m/s, from 2.5 to 4 second wind speed is 8 m/s and after that, wind speed gradually varies from 8m/s to 6 m/s. This change is shown in table 7. The loading condition is constant for all 6 second is kept constant at 27 Ω. The output power is continuously varying with the change in wind speed and change in load. The results shown in Figure 12,

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indicates the transient condition applied for WECS fixed gain and advanced controllers to compute required quantities from WECS. The value of voltage, current and power is demonstrated in Fig. 12 with incorporation of VCPO MPPT algorithm.

Analysis for Variable Wind Speed with Variable Loading Condition

We have applied variable wind speed with variable loading conditions for all three types of controllers CPI, GSPI, and GG controllers.

Table 8. Variation in Wind speed

Wind speed in m/s	6	6	7	7	8	8	6	6
Time	0	0.5	1.5	2.5	3.5	4	5	6

Table 9. Change in load/resistance

Time	0	1	2	3	4	5	6
Load Resistance in Ω	27	25	25	20	20	15	15

The real time applications of the WECS it is found that wind speed is continuously changing and loading is also changing. Therefor analysis of the WECS with VCPO is done for variable wind speed and variable loads. The Fig 13 shows that for 0.5 second wind speed is at 6 m/s and till 2.5 second it is of 7 m/s, from 2.5 to 4 second wind speed is 8 m/ to 6 m/s. This change is shown in table 8. The loading condition is constant for all 6 second is kept constant at 27 Ω. With the change in wind speed loading is also changing. Table 9 indicates the change in load and loading is varying in the form of 27Ω, 25Ω, 20Ω, and 15 Ω simultaneously. In Figure. 13 output power is varying with the change in wind speed and loading conditions, the small transients is observable when the load is changing. But for DC link voltage all three controllers are giving a continuous stable response. From the crucial analysis of Figure. 13, it is observable that with the implementation of the variable current P&O algorithm showing effective response in variation in wind speed and change in loading conditions and adoptive topologies of the controllers

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are addressing the effectiveness compare to fixed gain PI controller. The small-scale wind energy conversion system works effectively at maximum power point under the change in wind speed and change in load as well.

Simulation Results for Variable Step P&O MPPT Method

For this section, we have applied the variable step P&O algorithm for small-scale wind energy conversion systems. WECS is simulated in PSIM for various permutation and combinations for fixed gain (CPI), GSPI, and good gain PI controllers as shown in Figure. 3(b), 5(b), and 7(b) respectively, and analysis of that cases discussed as earlier is done based on output power, DC link voltage and output current for fixed gain and advanced controllers.

Analysis for Fixed Wind Speed 7m/S for Constant Loading Condition at 15 Ω with Variable Step P&O Algorithm (Mechanical P&O)

Table 10. Response for fixed wind speed 7m/s for constant loading condition at 15 Ω with variable step P&O algorithm

PI controlling technique	Voltage from generator (RMS) in V	Current from generator (RMS) in A	Voltage after rectification in V	Voltage after boost in V	Power drawn in W	Output voltage in V	Load Resistance in Ω
Fixed gain PI	64.0	32.4	83.7	222.4	3297.8	222.4	15
GSPI	60.1	26.7	78.4	196.4	2570.5	196.4	
Good Gain PI	56.8	28.2	74.2	197.4	2598.0	197.4	

This case presents, Small scale WECS with incorporation of the variable step P&O algorithm for Fixed gain, GSPI, and good gain PI controllers is tested for the loading condition at 15 Ω and wind speed at 7m/s.

Fig. 14 indicates the results of output power, voltage, and current for Fixed gain (CPI), GSPI, and GG. For the 3KW stand-alone WECS with variable step P&O algorithm fixed gain PI controller is giving 3297.8W output power, GSPI is giving 2570.5W and the good gain PI controller is showing 2598.0W for fixed wind speed 7 m/s and loading condition 15 Ω. Table 10 represents

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the various quantities of the WECS for fixed wind speed for the fixed gain PI, the GSPI, and the GG PI controllers.

Analysis for Fixed Wind Speed 7m/S for Constant Loading Condition at 20 Ω with Variable Step P&O Algorithm (Mechanical P&O)

Likewise, this case incorporates wind speed is still kept constant at 7 m/s loadings is changes to 20 Ω for all three controllers with the variable step P&O algorithm for stand-alone WECS.

Table 11. Response for fixed wind speed 7m/s for constant loading condition at 20 Ω with variable step P&O algorithm

PI controlling technique	Voltage from generator (RMS) in V	Current from generator (RMS) in A	Voltage after rectification in V	Voltage after boost in V	Power drawn in W	Output voltage in V	Load Resistance in Ω
Fixed gain PI	64.8	30.5	85.0	251.1	3152.0	251.1	20
GSPI	63.4	21.7	83.3	208.8	2177.6	208.8	
Good Gain PI	57.5	26.6	75.1	222.4	2471.8	222.4	

For constant wind speed of 7m/s and loading condition for 20 Ω Figure 15. indicates the simulation results for output power, DC link voltage and current for three controllers. Table 11 carries various quantities for WECS. The fixed gain PI providing 3152.0W, GSPI providing 2177.6W, and GG providing 2471.8W.

Analysis for Fixed Wind Speed 7m/S for Constant Loading Condition at 25 Ω with Variable Step P&O Algorithm (Mechanical P&O)

Similarly, as in the above mentioned case, we change the loading conditions from 20 Ω to 25 Ω for CPI, GSPI, and GG controllers.

For this case fixed gain PI controller shows 2224.4W, GSPI shows 2390.3W and 2411.8W output power. All other responses of voltage and current are tabulated in table 12. Results are plotted in Figure. 16. for load resistance 25

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Ω, the output power is increase for the fixed wind speed 7m/s for the same small-scale WECS implemented with variable step P&O algorithm.

Table 12. Response for fixed wind speed 7m/s for constant loading condition at 25 Ω with variable step P&O algorithm

PI controlling technique	Voltage from generator (RMS) in V	Current from generator (RMS) in A	Voltage after rectification in V	Voltage after boost in V	Power drawn in W	Output voltage in V	Load Resistance in Ω
Fixed gain PI	66.0	28.2	86.6	271.0	2934.5	271.0	25
GSPI	65.5	18.3	86.5	216.7	1877.9	216.7	
Good Gain PI	58.4	24.2	76.4	239.2	2286.3	239.2	

Analysis for Fixed Wind Speed 7m/s for Constant Loading Condition at 27 Ω with Variable Step P&O Algorithm (Mechanical P&O)

The variable step P&O algorithm is implemented with Fixed Gain and advanced controllers like GSPI and Good gain PI controllers for fixed wind speed 7 m/s and loading at 27 Ω. Figure. 17 shows the simulation results of output power, voltage, and current for CPI, GSPI, and GG.

Table 13. Response for fixed wind speed 7m/s for constant loading condition at 27 Ω with variable step P&O algorithm

PI controlling technique	Voltage from generator (RMS) in V	Current from generator (RMS) in A	Voltage after rectification in V	Voltage after boost in V	Power drawn in W	Output voltage in V	Load Resistance in Ω
Fixed gain PI	64.8	30.5	85.1	216.8	3134.3	216.8	27
GSPI	66.0	17.2	87.3	218.7	1775.0	218.7	
Good Gain PI	58.7	23.7	76.7	246.0	2240.0	246.0	

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This analysis demonstrates four cases for VSPO MPPT algorithm implemented for 3kW WECS. The analysis is done for permutations and combinations of wind speed and load. Sections 6.2.1-6.2.4 indicates the simulation results for the fixed wind speed 7m/s for the constant loading conditions like 15Ω, 20Ω, 25Ω, and 27Ω for The fixed gain PI, the GSPI, and the good gain PI controllers. The simulation results are taken based on various parameters of WECS like output power, DC link voltage and output current. Various quantities of the WECS is taken into consideration in the tabular format. From the critical analysis it is shows that for the steady state conditions VCPO algorithm showing effective results. The adaptive techniques address the limitations of the fixed gain PI controllers.

Analysis for Variable Wind Speed at Constant Loading Condition 27 Ω

The wind is changing every time. So for change in wind speed system should be tested. Therefore, we have applied a change in wind speed for fixed loading condition 27 Ω for all three types of controllers CPI, GG, and GSPI.

Table 14. Response for variable wind speed at constant loading condition 27 Ω

Wind speed in m/s	6	6	7	7	8	8	6	6
Time	0	0.5	1.5	2.5	3.5	4	5	6

This analysis represents the variable change in wind speed for constant loading condition for small scale WECS. The wind speed for first 0.5 second is at 6 m/s and till 2.5 second it is of 7 m/s, from 2.5 to 4 second wind speed is 8 m/s and after that, wind speed gradually varies from 8m/s to 6 m/s. This change is shown in table 14. The loading condition is constant for all 6 second is kept constant at 27 Ω. The output power is continuously varying with the change in wind speed and change in load. The results shown in Figure 18, indicates the transient condition applied for WECS fixed gain and advanced controllers to compute required quantities from WECS. The value of voltage, current and power is demonstrated in Fig. 18 with incorporation of VSPO MPPT algorithm.

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Analysis for Variable Wind Speed with Variable Loading Conditions

For the small-scale wind energy conversion system, we have applied variable wind speed with variable loading conditions for all three types of controllers CPI, GSPI, and GG controllers.

Table 15. Variation in wind speed

Wind speed in m/s	6	6	7	7	8	8	6	6
Time	0	0.5	1.5	2.5	3.5	4	5	6

Table 16. Change in loading condition

Time	0	1	2	3	4	5	6
Load Resistance in Ω	27	25	25	20	20	15	15

The real time applications of the WECS it is found that wind speed is continuously changing and loading is also changing. Therefor analysis of the WECS with VCPO is done for variable wind speed and variable loads. The Figure 19 shows that for 0.5 second wind speed is at 6 m/s and till 2.5 second it is of 7 m/s, from 2.5 to 4 second wind speed is 8 m/ to 6 m/s. This change is shown in table 15. The loading condition is constant for all 6 second is kept constant at 27 Ω. With the change in wind speed loading is also changing. Table 16 indicates the change in load and loading is varying in the form of 27Ω, 25Ω, 20Ω, and 15 Ω simultaneously. In Figure. 19 output power is varying with the change in wind speed and loading conditions, the small transients is observable when the load is changing. But for DC link voltage all three controllers are giving a continuous stable response. From the crucial analysis of Figure. 30, it is observable that with the implementation of the variable current P&O algorithm showing effective response in variation in wind speed and change in loading conditions and adoptive topologies of the controllers are addressing the effectiveness compare to fixed gain PI controller. The small-scale wind energy conversion system works effectively at maximum power point under the change in wind speed and change in load as well.

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Comparative Analysis of Fixed Gain and Advanced Controllers

This section represents the comparison between variable current P&O algorithm and Variable Step P&O algorithm for maximum power point tracking of WECS for the fixed gain PI controller and other adoptive controller techniques like the GSPI and the good gain PI controller.

The first bar of every bar charts represents the quantities for the fixed gain PI controller, the second bar indicates the quantities for the Gain Scheduling PI controller and the third bar is for the good gain PI controller.

The analysis demonstrates the comparison between VCPO and VSPO considering voltage across the load, current drawn by the load and power drawn by the load for small-scale WECS simulated for the fixed gain PI and other adoptive controller techniques like the GSPI and the good gain method for various wind speeds of 6m/s, 7m/s, and 8 m/s.

Figure. 20(a) shows the results for the variable current P&O algorithm from that figure it is visible that for the variable current P&O algorithm the Gain Scheduling PI controller is giving the maximum output power and addressing the limitations of the Fixed gain PI controller.

From the Figure. 20(b) it is observing that the advanced controllers are showing effective results for the variable step P&O algorithm for the stand-alone WECS and adaptive controllers are overcoming the limitations of the fixed gain PI controller.

TRANSIENT ANALYSIS

The stability of any system is checked by the transient performance of that particular system with the sudden change in input variables. Overshoot is a reference to the transient values of any parametric measurement that exceeds its steady-state or final value during its transition from one value to another. In this section, we have done the transient analysis of small-scale Stand-alone WECS for the fixed gain and advanced controllers like GSPI and good gain PI controller. For our system, we have applied a sudden change in wind speed for VCPO and VSPO for the fixed gain and adaptive topologies of the controllers as well.

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Table 17. Percentage overshoot for the sudden change in wind speed for variable current P&O algorithm

Overshoot for variable Wind speed for variable current P&O			
	Fixed Gain	**GSPI**	**Good Gain**
Load Voltage	2.1%	3.4%	2.0%
Load Current	3.4%	2.7%	2.2%
Load Power	7.8%	1.6%	6.8%

Table 18. Percentage overshoot for the sudden change in wind speed for variable current P&O algorithm

Overshoot for variable Wind speed for variable step P&O			
	Fixed Gain	**GSPI**	**Good Gain**
Load Voltage	2.7%	0.17%	3.9%
Load Current	3.8%	2.4%	4.3%
Load Power	8.7%	2.3%	9.2%

For the transient analysis we have applied the wind speed 6m/s for the first 1 second and it is changing 7m/s for another 1 second. The simulation results of the fixed gain PI controller, GSPI, and good gain PI controller for the sudden change in wind speed are shown in the figures, the Figure 21(a) shows the effect of sudden change on WECS implemented for variable current P&O algorithm whereas Figure 21(b) indicates the simulation results of the sudden change in wind speed on WECS with the incorporation of the variable step P&O algorithm. The percentage overshoot for VCPO and VSPO for various controller techniques are in the tabulated form considering load voltage, load current, and load power. Table 17 representing the percentage overshoot for the variable current P&O algorithm and table 18 showing the percentage overshoot for the variable step P&O algorithm. From the critical transient analysis, it is observing that the adaptive topologies for the controller addresses the limitations of the fixed gain controller even in the transient condition for WECS.

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CONCLUSION

The simulation and analysis for stand-alone WECS are performed with a change in wind speed and change in DC load. The wind speed is considered by measurement of the wind speed at the height of 10 m from the ground the simulation is performed with DC to DC converter with the incorporation of an MPPT algorithm. The system is tested for the sudden change in wind speed and the variable change in wind speed for VCPO and VSPO MPPT methods. The system is also simulated with the fixed gain controller, the GSPI, and the good gain method. From the above cases following concluding remarks are observed.

- The variable current P&O algorithm is implemented for stand-alone WECS. The results are achieved by generating reference current from the MPPT algorithm. The algorithm shows effectiveness for change in climatic conditions by changing the wind speed. The DC link voltage is regulated by the incorporation of the DC-DC converter. The system works satisfactorily for the DC load with permutations and combinations of wind speed and DC load.
- The variable step P&O algorithm is implemented for stand-alone WECS. The results are achieved by generating reference power from the MPPT algorithm. The algorithm shows effectiveness for change in climatic conditions by changing the wind speed. The DC link voltage is regulated by the incorporation of the DC-DC converter. The system works satisfactorily for the DC load with permutations and combinations of wind speed and DC load.
- The comparative analysis is done between VCPO and VSPO algorithms. VCPO MPPT algorithm shows significant results under variable wind speed but VSPO shows the effectiveness under fixed wind speed conditions.
- From the simulation analysis, the critical outcome in the context of effectiveness for both the algorithms is 98% in the case of power generation. The stand-alone system is implemented with fixed and advanced PI controllers like the GSPI, and the GG.
- To address the limitations of the fixed gain controller the GSPI is adopted. The effect of GSPI for the stand-alone WECS is observed under the variations in wind speed and change in DC load.
- In the case of the good gain method, it provides effective results in comparison with the fixed gain controller.

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- The value of the overshoot for load voltage, load current, and load power under variable wind speed for the VCPO and the VSPO MPPT algorithms is computed.
- The GSPI controller provides better results under the sudden change in wind speed and variable change in wind speed for stand-alone WECS for steady-state and transient conditions.

This system plays an important role when the grid connection is not feasible.

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APPENDIX 1

Parameter Used

PMSG: Power rating = 3.5kW, stator resistance = 56mΩ, d and q axis inductance = 1.6mH, number of poles = 8.

Value of L and C for boost converter:

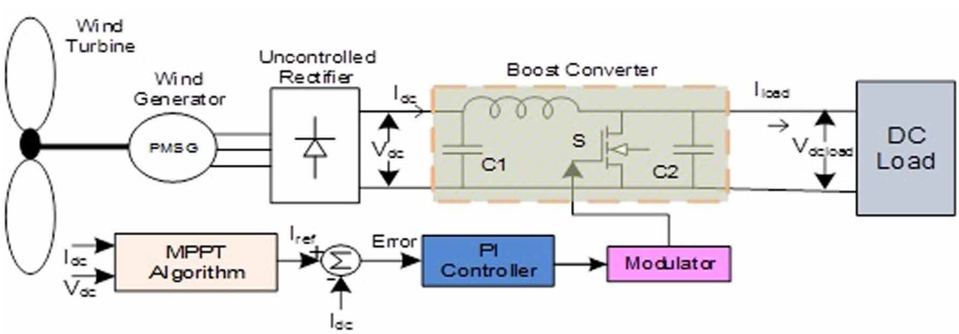
L=900uH and C_1=3.5mF & C2=400mF for variable current perturbation algorithm.

L=900uH and C_1=3.5mF & C2=23mF for Variable step P&O MPPT algorithm.

Switching frequency: f_s = 10 kHz

APPENDIX 2

Figure 1.



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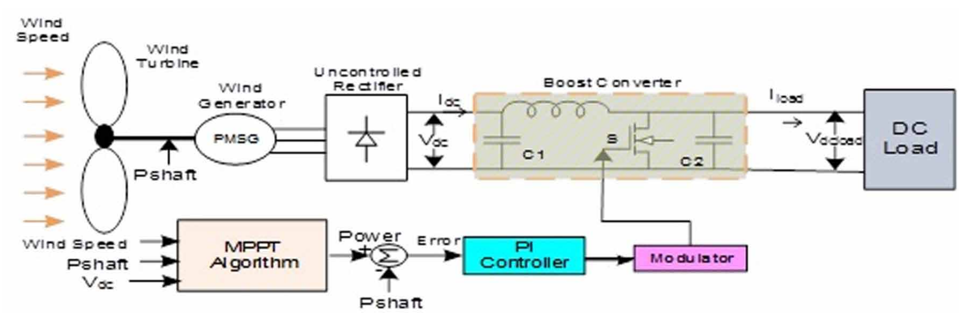

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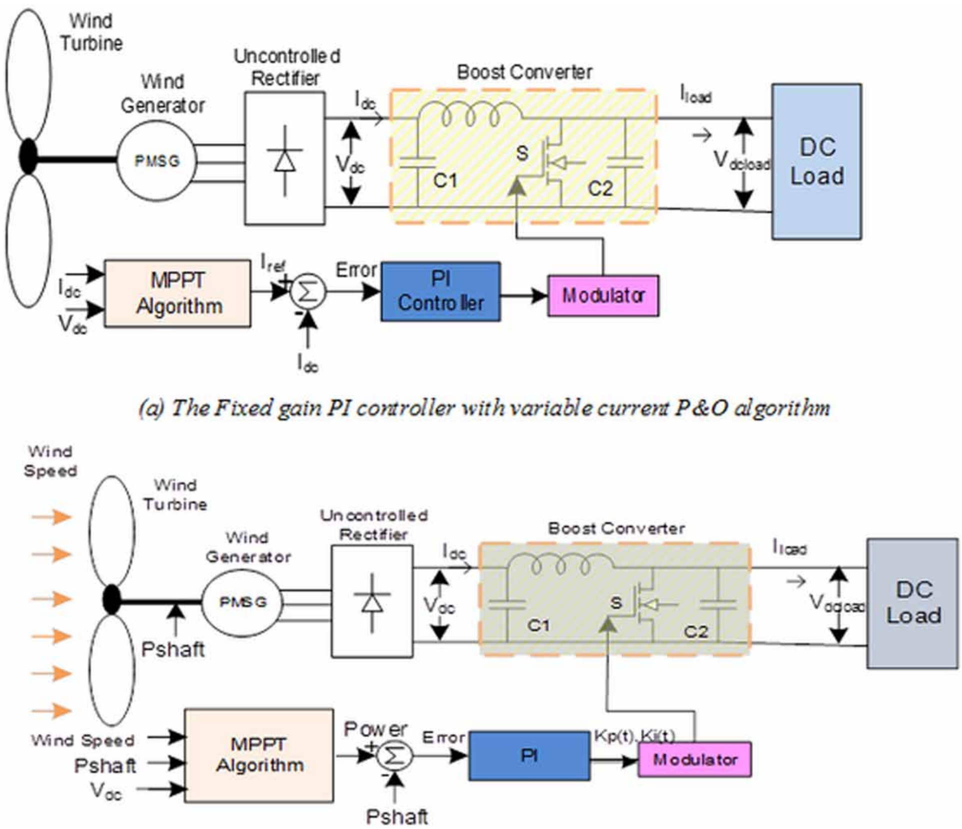
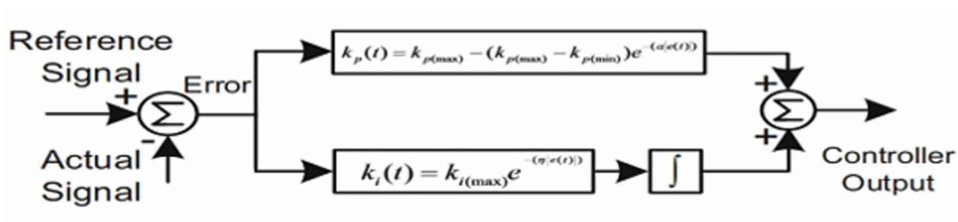


(a) The Fixed gain PI controller with variable current P&O algorithm

Figure 4.



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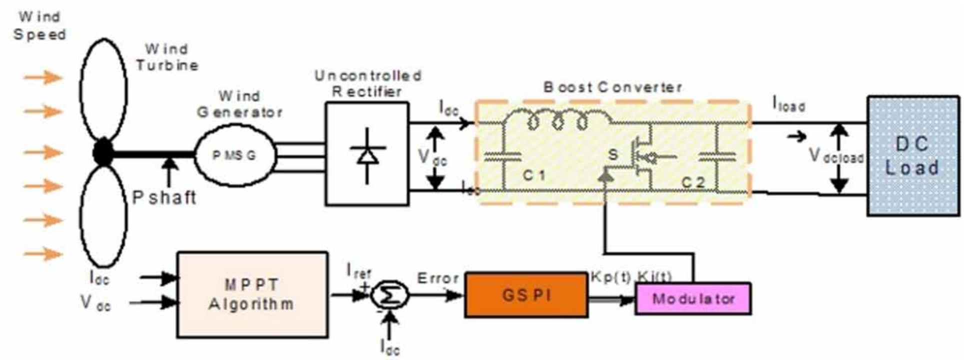
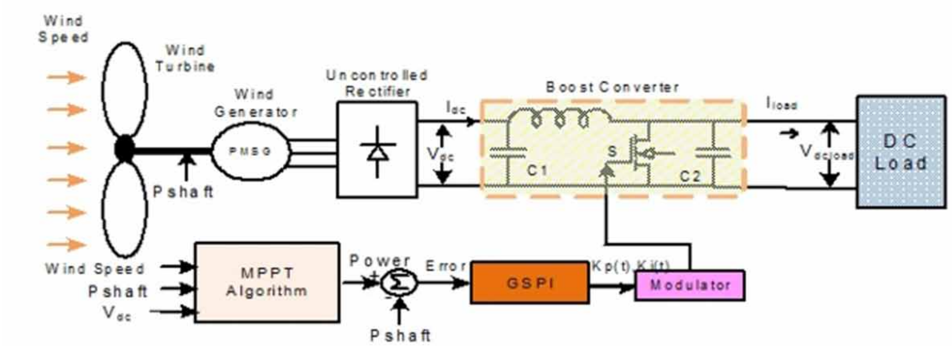


(a) Gain Scheduling PI controller with variable current P&O algorithm



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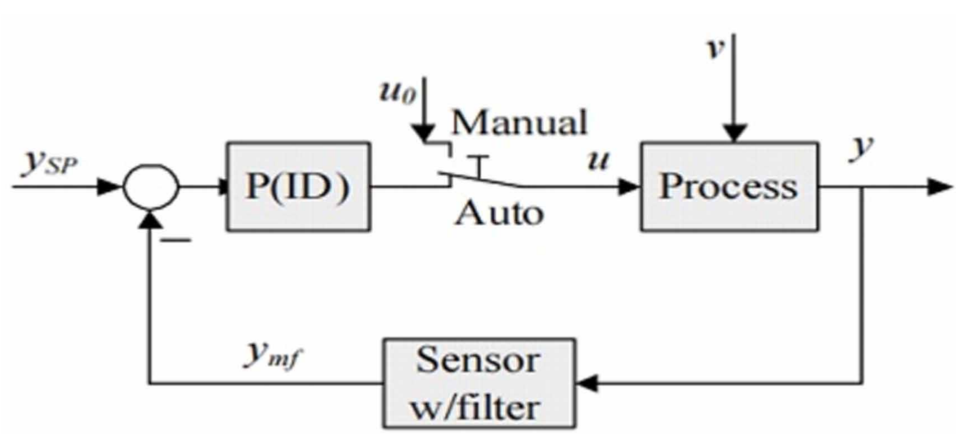

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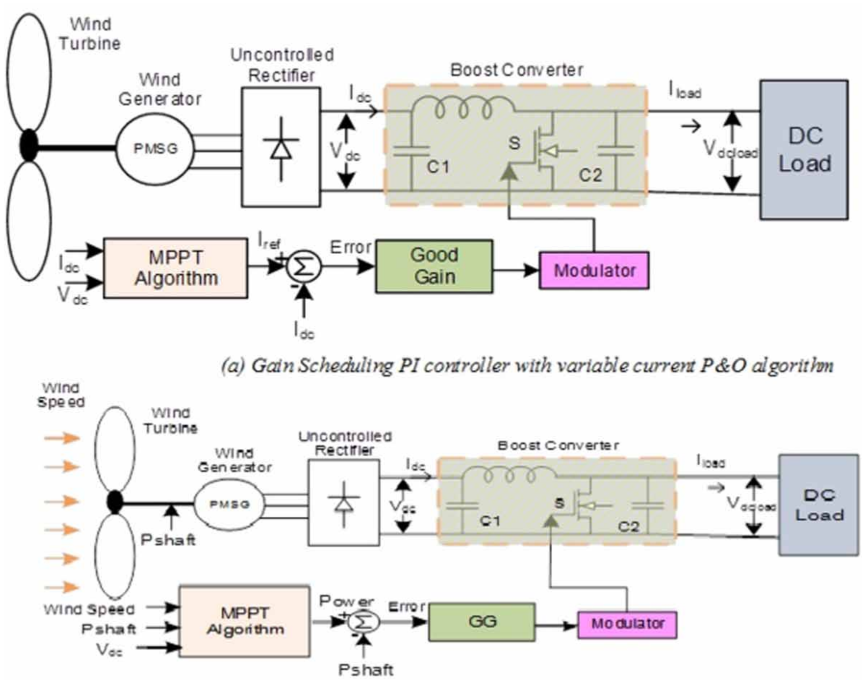

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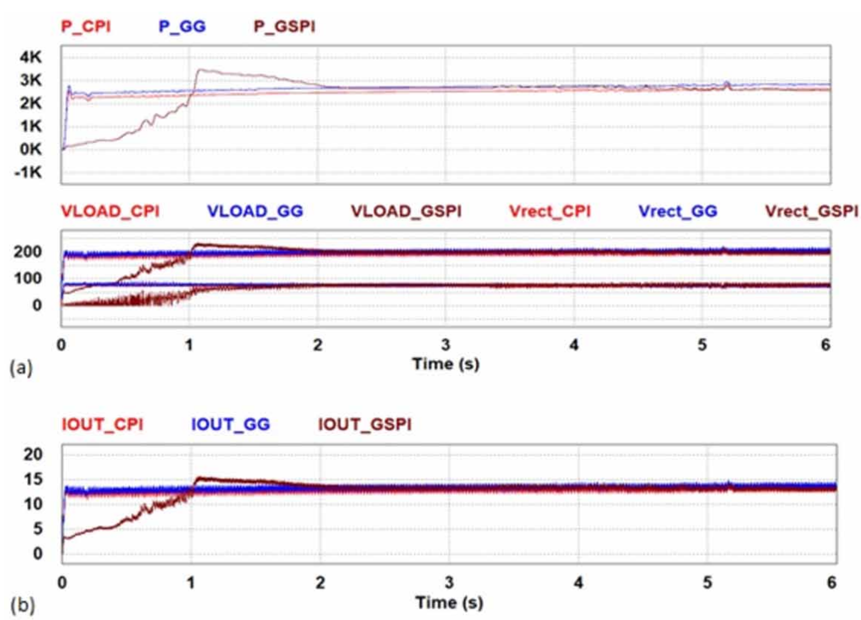

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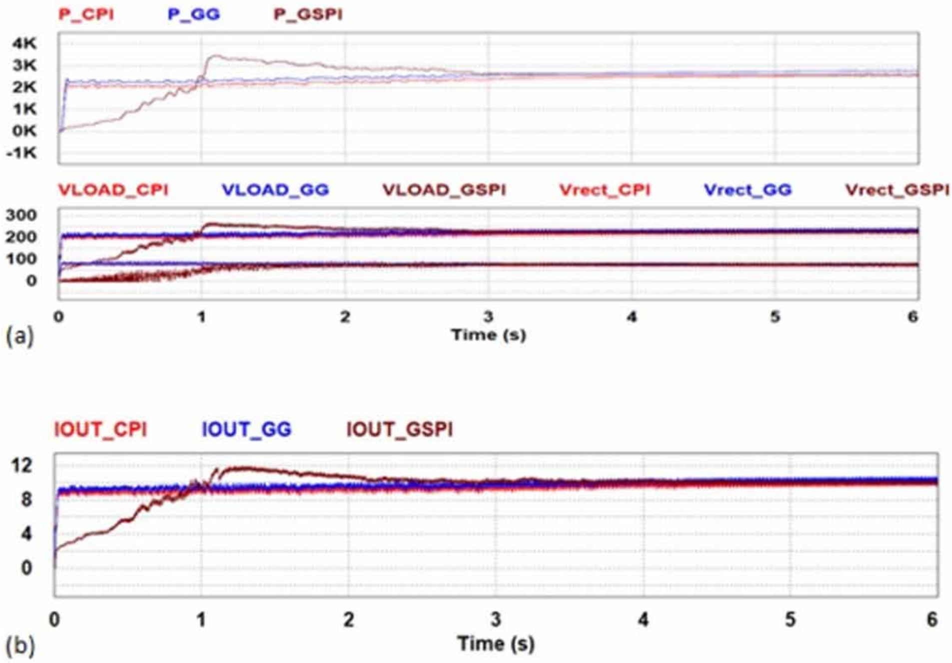

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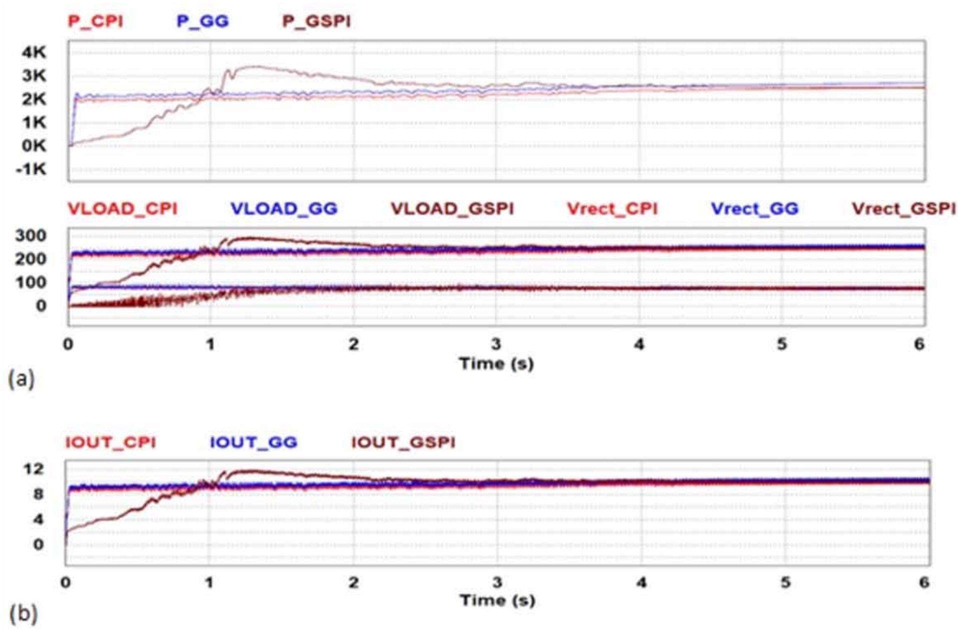

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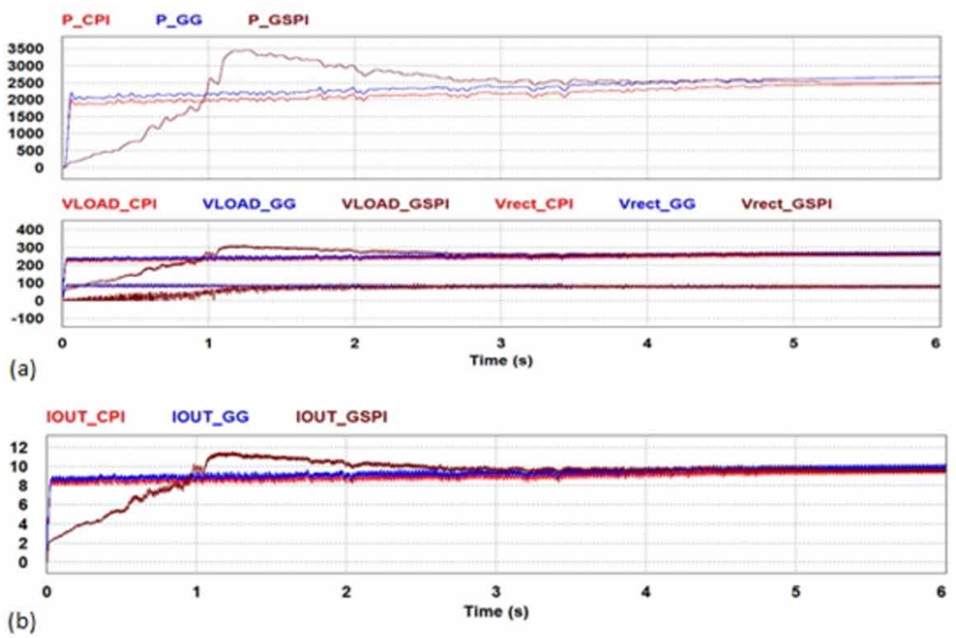
Figure 11.



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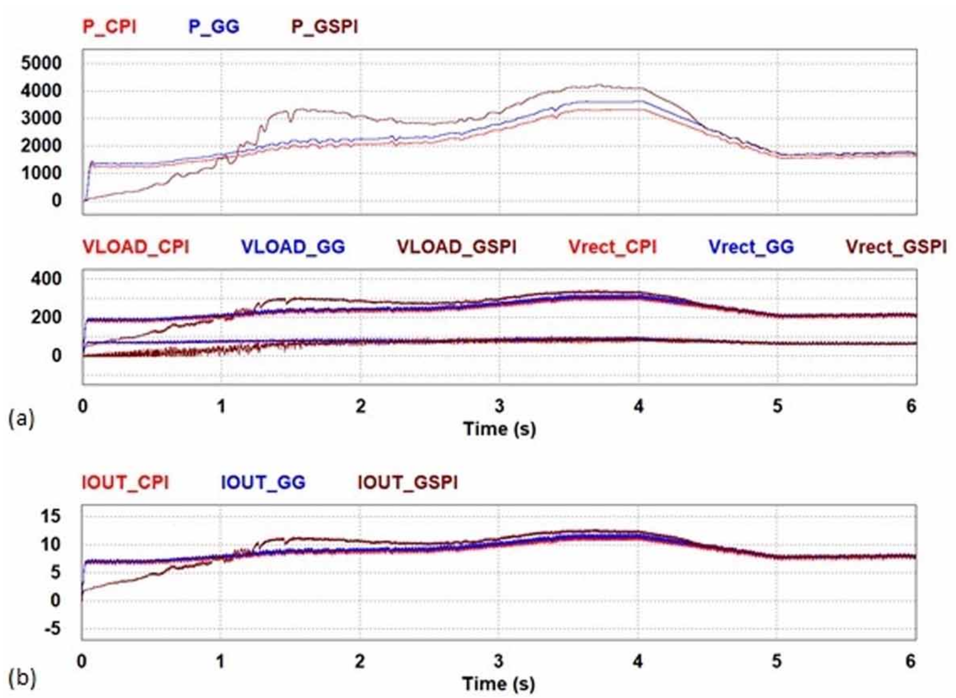

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Figure 13.

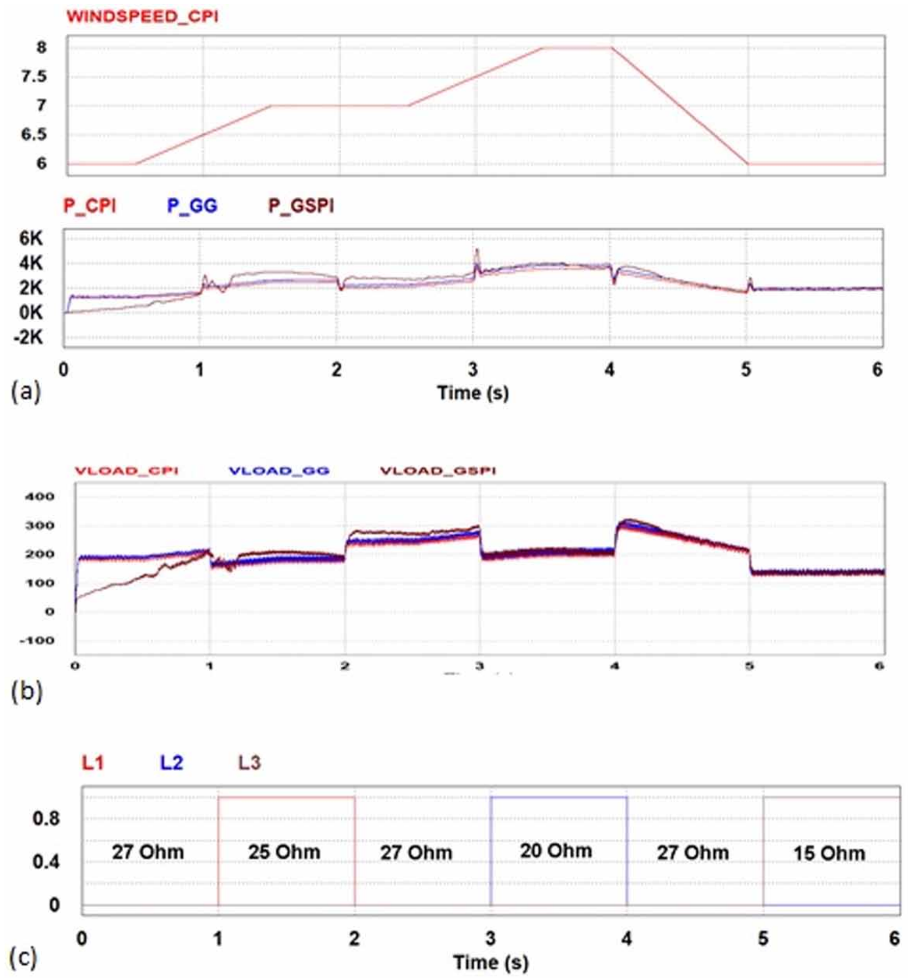

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Figure 14.

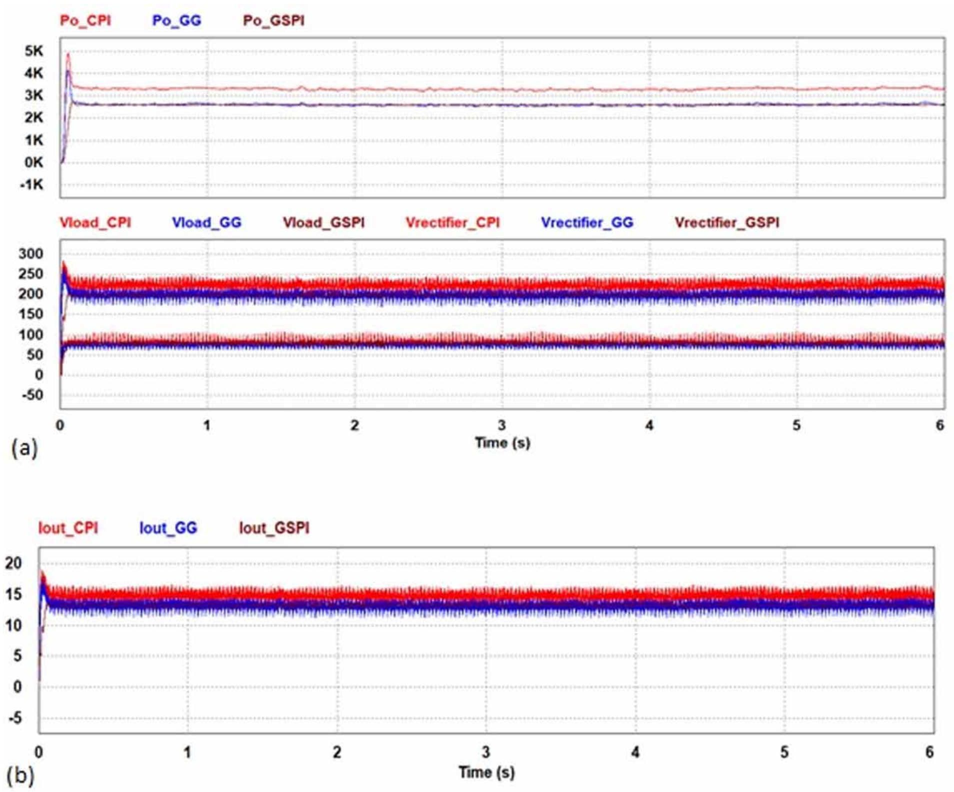

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Figure 15.

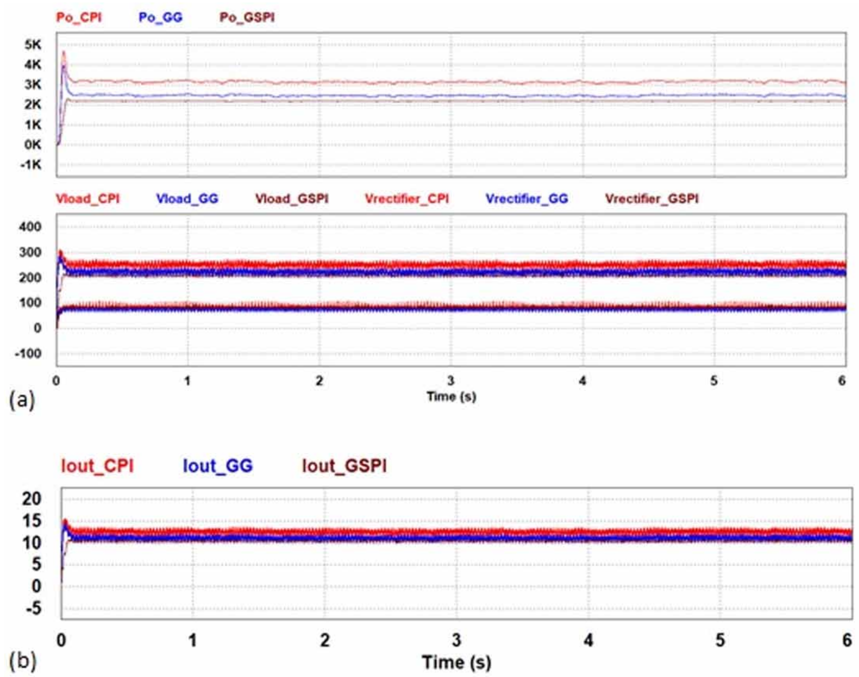

Figure 16.

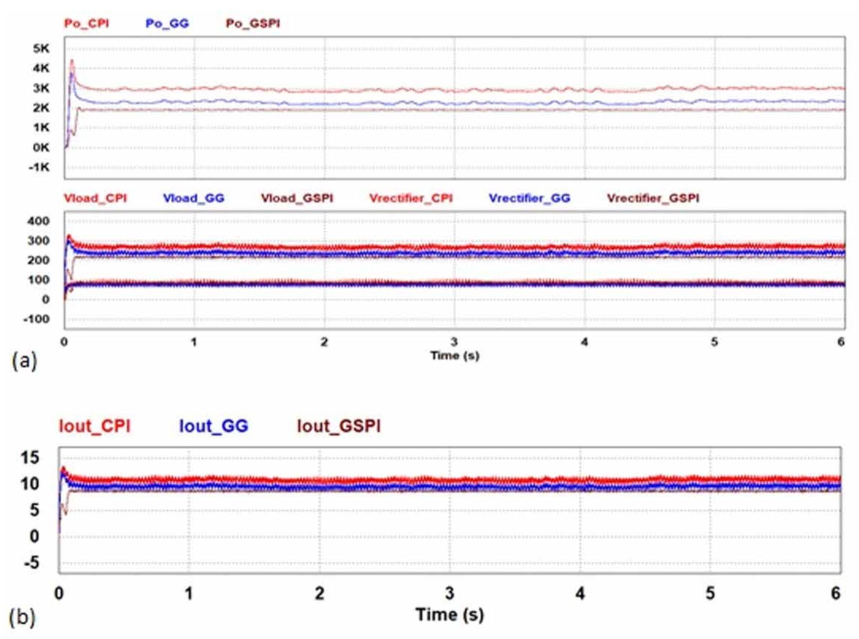

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Figure 17.

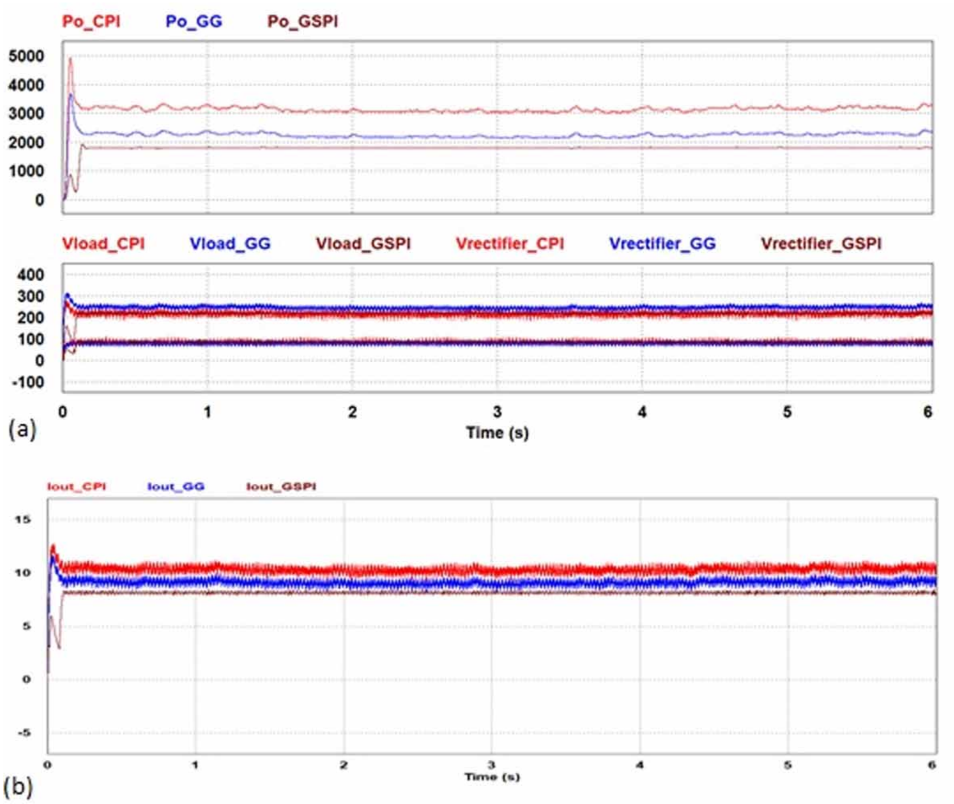

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Figure 18.

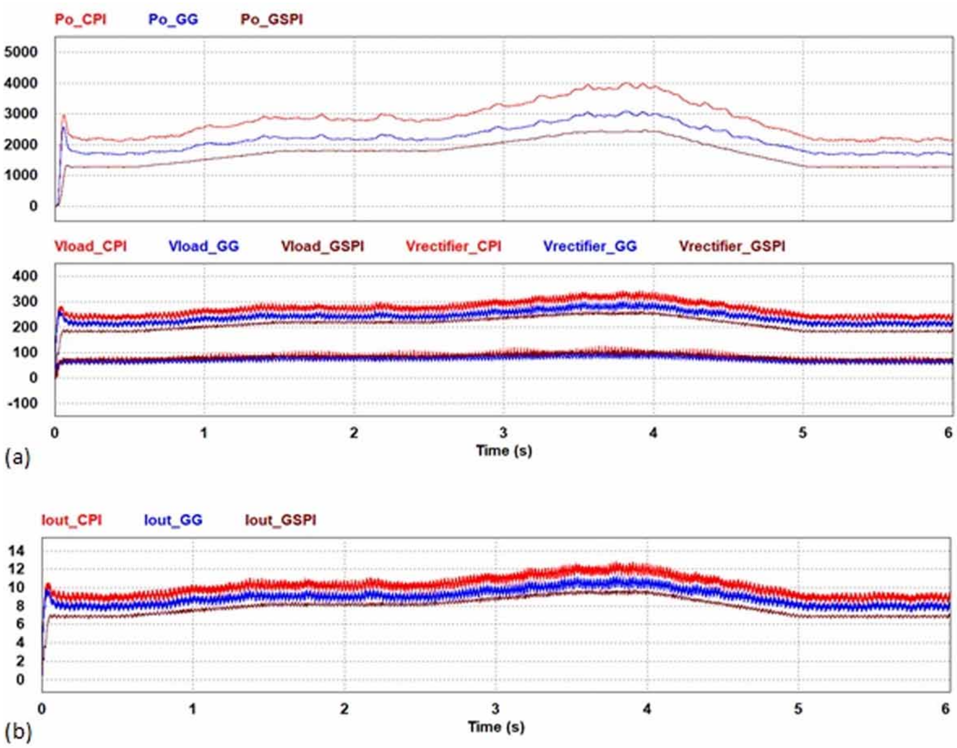

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Figure 19.

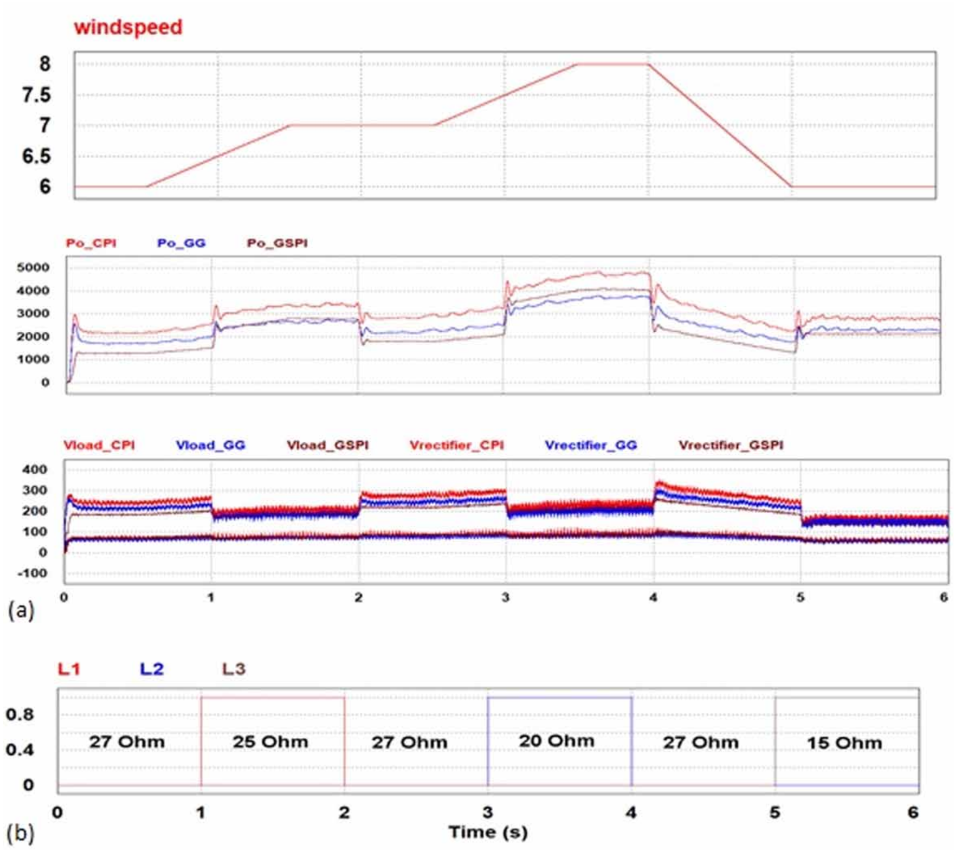

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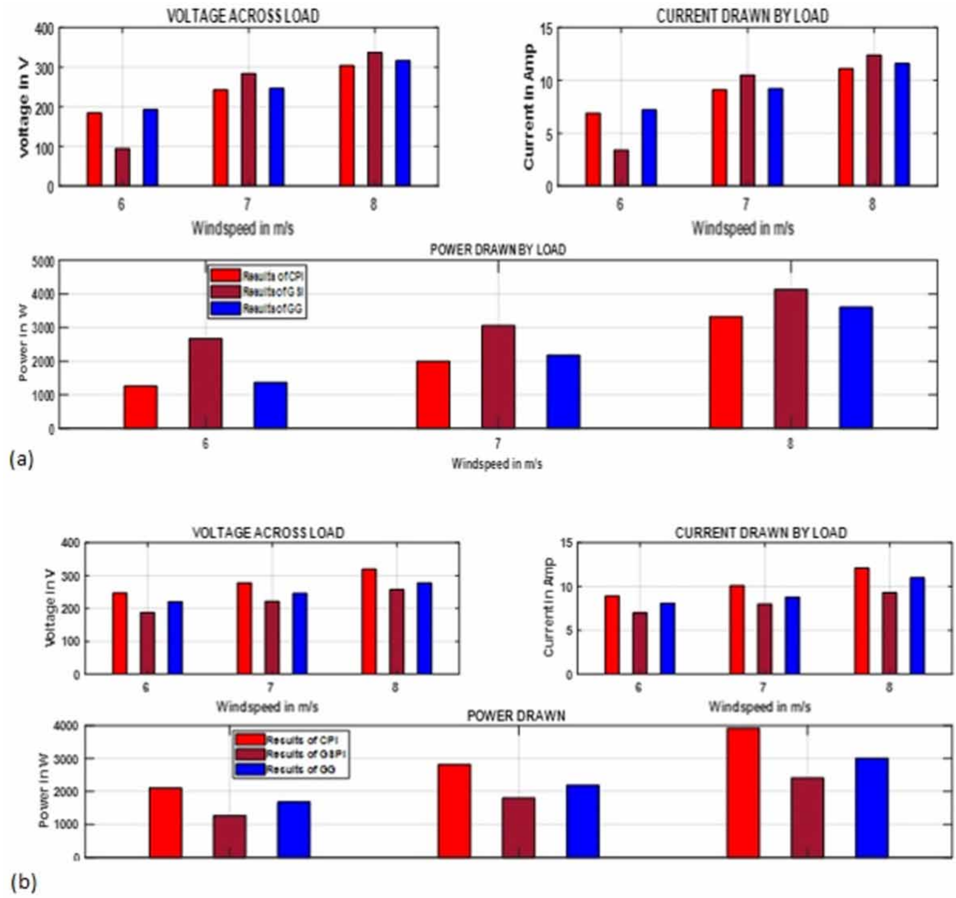
Figure 20.



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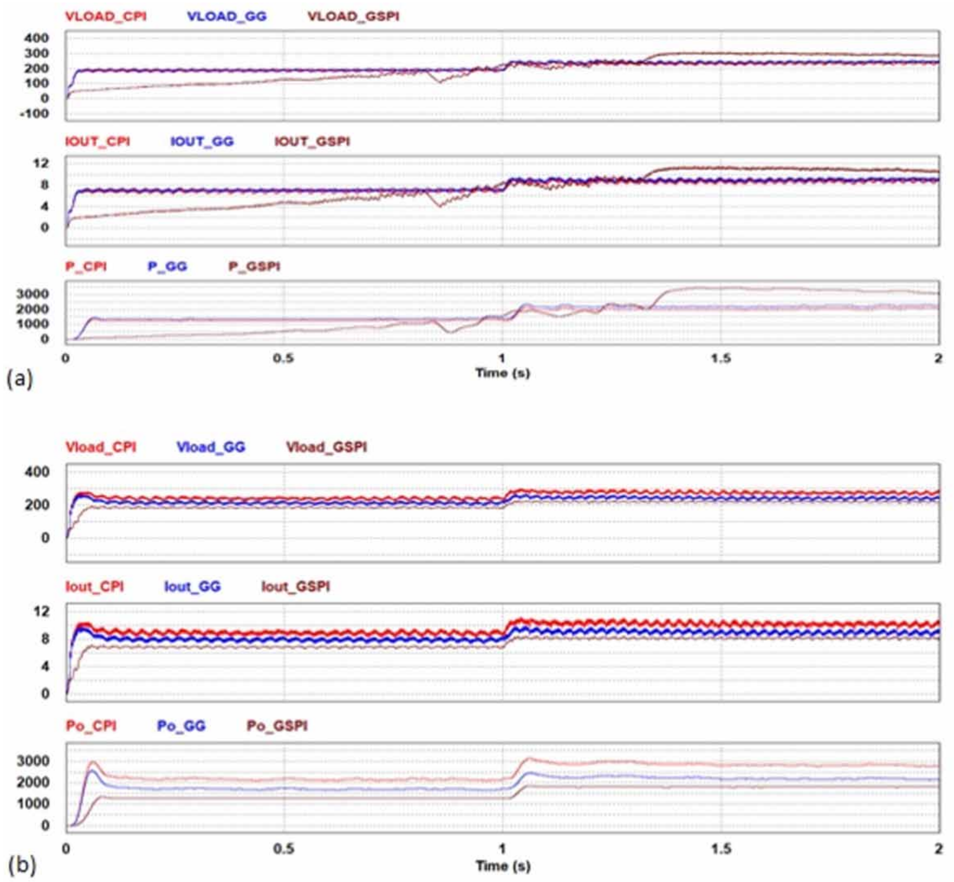

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Chapter 3
A Novel MS Excel Tool for Multi-Criteria Decision Analysis in Energy Systems

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ABSTRACT

Application of multi-criteria decision analysis (MCDA) methods to various aspects of energy systems is of significant interest. This chapter first proposes a simple yet user-friendly MS-Excel tool with four popular MCDA methods. The tool can be effectively used to apply MCDA techniques and to determine the rankings for the alternatives. This MS-Excel tool is made available on Mendeley data repository. The chapter explains the overall MCDA computational processes, algorithms, and provides details on using the tool itself with the help of two case studies to demonstrate its effectiveness and applicability.

INTRODUCTION

Due to technical advances, contemporary energy systems are increasingly getting complex with different energy sources and consumer types. This situation naturally poses challenges to system designers, researchers and policy makers due to too many variables, cost options, several possible options of

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combinations and configurations of system components. Then niche concepts such smart cities, circular economy, green technology concepts etc., suggest eco-friendly solutions to the designers. Then, regulatory standards and expectations in the use of energy sources and even materials in construction sector also pose additional challenges. Many of these technical advances such as fourth industrial revolution, opportunities and challenges have been dealt with various researchers over the years in wider areas of energy systems, transportation systems and construction of buildings etc. For instance, researchers have dealt with numerous, different computational strategies and domain aspects related to energy systems such as - identification of suitable renewable energy source, location of a power plant, optimal mix of energies to feed into the grid etc. Similarly, optimal design of transport systems has been explored with various computational approaches. Prominently design and construction of buildings with various environmental friendly, green materials and optimal configurations also have been considered by researchers. Specifically, smart cities are expected to be environmental friendly and thus developing energy resources to smart cities with minimal carbon footprint is imperative (KS Sastry, Musti, 2020a). Whatever may be the area of study, use of optimization studies has become a norm in the planning and design phases of modern systems. Specifically, such studies have identified the need of using multi-objective optimization criteria, since many of the variables and parameters are very different from one another. For instance, some of the variables in energy systems such as – levelized cost, capacity factor, requirement of land area, environmental friendliness, socio-economic impact etc., are different from one another; and even some of such variable may not have measurable units. Thus, it is not always possible to attach units of measurement to every parameter. Similarly, parameters like professional perceptions and/or opinion of users on aesthetics etc., cannot be measured with known units and rather are represented with a number on a scale, let us say 0 to 10. This has led to the use of Multi-Criteria-Decision-Making (MCDM) tools in decision making process or even in the case of optimization processes. In the recent past, MCDM tools have become a standard choice where participating variables are dissimilar from one another. Several different MCDM approaches do exit that can address multiple conflicting objectives and criteria. Nonetheless, not all MCDM approaches are suitable for use for all the situations, and/or research problems.

Given the fact of availability of different MCDM methods, there will always be a question on selection of appropriate method for a given area of study. Further, a classical question always comes into the minds of users

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about the possible outcome if all these methods applied independently to a given problem. The fact is that several published articles have described the computational processes and application of these methods; and even comparison of some methods with another. A few papers have suggested the use of MS-Excel as a platform to implement some of the computational approaches and a very few spreadsheets based tools are available for specific methods. That said, it can be seen that there is no open-source software tool that provides a computational platform for researchers or policy makers to understand the nature of methods and/or to study the effectiveness of these MCDM. From the above, a few aspects can be understood.

- Energy researchers and policy makers have a significant interest in MCDM
- MS-Excel is being used as a platform to implement the MCDM
- Application of MCDM in energy studies is of significant interest to many
- At present, there is no single software tool that can apply different MCDM
- There is an immense need to develop such software tool to assist researchers and policy makers in applying MCDM.

In view of the above, this chapter proposes design and development of a spreadsheet tool that can potentially demonstrate a few selected MCDM. The reminder of this chapter is divided into different sections with appropriate titles. The next section presents a brief literature review and then highlights the need for developing a MS-Excel tool for MCDM. Then, algorithms of a few selected MCDM are presented for the sake of completeness and the following section illustrates the implementation of these algorithms in a MS-Excel spreadsheet. The MS-Excel tool can be downloaded from the Mendeley database https://data.mendeley.com/datasets/zjckp3b259/1 (Musti, 2021). Then two simple cases studies are considered in the case studies section to explain the features, effectiveness and end-use of developed spreadsheet tool. Then a thorough discussion is taken up to explore further prospects in this area and after that conclusion is presented.

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LITERATURE REVIEW

Over the years, several authors have treated these computational approaches for different purposes and applications. Obviously, MCDA (multi-criteria decision analysis) is an effective approach to help planners, designers and managers in dealing with the various technical, non-technical and financial processes to obtain the best solutions when multiple, yet conflicting objectives have to be achieved. To start with, researchers have thus far used different terminology, but two phrases MCDA and MCDM (multi-criteria decision methods) have been used in most cases. Thus, these two phrases are synonymous to each other. Sometimes using several different phrases by various works can be confusing (Kumar et.al., 2017; Rigo et.al., 2020) to the readers. In reality, MCDA is a singular term, which represents a process and MCDM is a plural term which represents a set of different computational methods. This chapter uses both the terms based on the context.

MCDM can be broadly classified in three ways. Firstly, based on the mathematical nature of the method, secondly, on the problem solving methodology; and thirdly the combination of the first and second approaches. Some of the prominent approaches of MCDM are: Weighted Sum Method (WSM), Weighted Product Method (WPM), Elimination and Choice Translating Reality (ELECTRE), Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), Choquet Integral and VIKOR etc. WSM, WPM, AHP and TOPSIS are specifically popular in the areas of energy planning, environmental Studies, structural optimization and process optimization etc. Essentially these all methods are solution search techniques, yet completely different from the conventional optimization techniques.

The landscape of MCDM research has different areas such as – pure mathematical treatment of algorithms of the methods themselves, application of MCDM to planning of various systems (such as energy systems), post solution analysis (such a s feasibility, applicability and sensitivity analysis, fitness analysis), Life Cycle Sustainability Assessment (LCSA) and several others. However, it should be noted that over the last decade few tens of hundreds of research articles have been published in this area and thus it can be quite time and space consuming to provide a detailed account on the categories. Naturally, a several review articles have appeared as well (Diakoulaki (2019); Kumar et.al., 2017; Wulf et. al., 2019; Rigo et.al., 2020) and their contributions pointed to ever rising interest in applying MCDM

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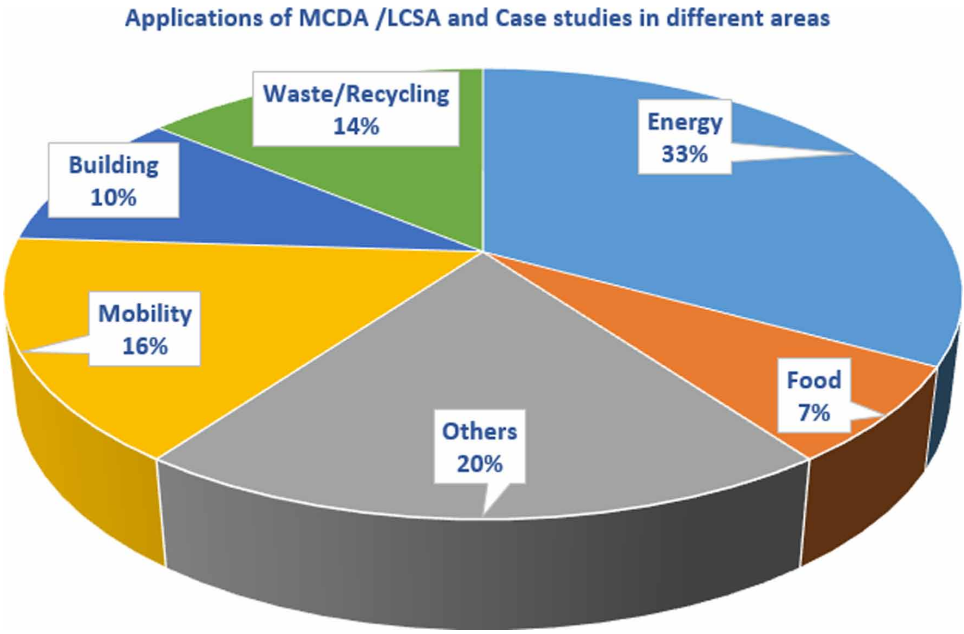
specifically to various aspects of energy systems. Wulf et. al. (2019) provided details of number of research articles over the last 20 years in different areas and figure 1 shows the same through a pie-chart.

Figure 1. Different areas in which MCDM were applied
Source: Wulf (2019)



From figure 1 it can be seen that about a third of the total articles are in the area of energy systems and thus it can be safely noted that this area is of significant interest to researchers specifically in applying the MCDM. On the other hand, Estevez (2021) provided a breakup of various specific sub-topics of energy systems in which MCDM were applied. This information is shown in figure 2 through a pie-chart.

It can be seen that selection of type of renewable energy source is of significant interest to researchers. The reasons behind this interest are many. Firstly, over the years, levelized costs of renewable energies have been coming down drastically. Secondly, technological advances in core engineering areas and even multi-faceted, digital advances such as fourth industrial revolution etc., have pushed the capacity addition of renewable energies to a great extent. Thirdly, new frontiers of renewable energy sources such as battery

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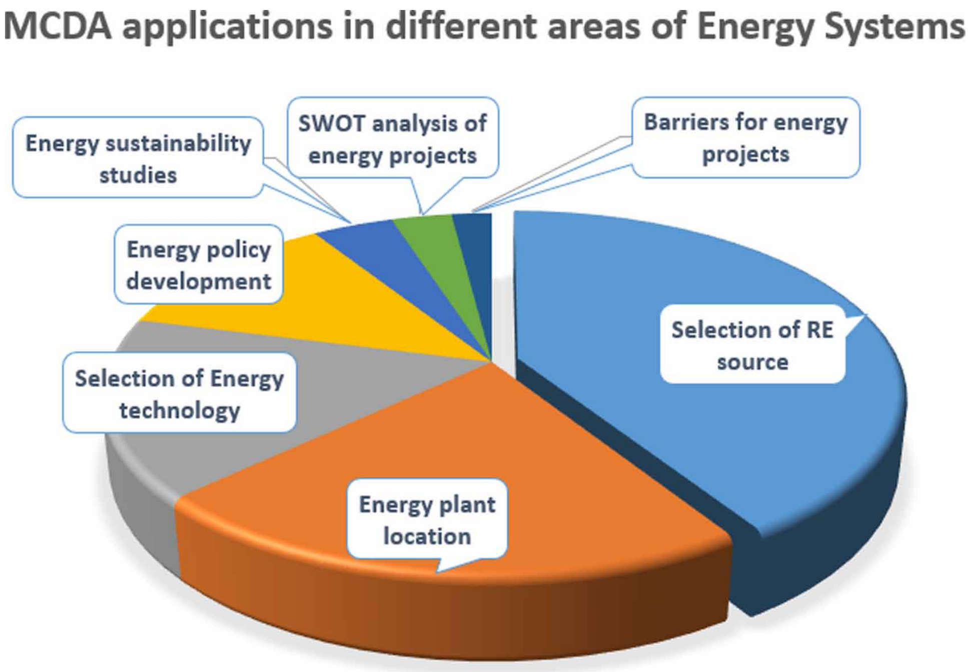
storages, Hydrogen etc., have been explored well. However, assessment of energy projects can be quite complex as LCSA studies have to be undertaken. Naturally, a good number of researchers have focused on LCSA studies in energy systems area. Wulf et. al (2019) state that

Until the end of 2018, 258 publications can be found, from which 146 include a case study. The highest number of publications appeared between 2016 and 2018 and, compared to the years before 2016, the number of authors has increased. However, in recent years the focus has been more on case studies than on methodological aspects of LCSA.

Figure 2. Specific sub-topics of energy systems in which MCDM were applied
Source: Estevez (2021)



Interestingly, most research articles have come a few countries. Rigo et.al (2020) pointed that a significant number of articles have come from three countries – China, Iran and Turkey in the area of energy management. Estevez (2021) et al felt that most papers are from Asia and Europe and that more papers need to be seen from Latin America, Africa and other developing nations

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where scope for renewable energy penetration is high. However, a majority of the papers did not take up socio-economic and environmental issues when they applied MCDM to renewable energies. In fact, to add renewable energy to the existing capacity requires a lot of planning and in-depth analysis, that includes the complete LCSA.

From the above, it may seem as though the area of applying MCDM to energy systems might have gotten over saturated. The reality is that both MCDM and energy system areas are quite complex in their individual strides and thus a several aspects still need to explored. Some of the aspects such as land use, LoCE, LCSA and end-use and grid connecting, load following, wider acceptability from stakeholders are not yet included simultaneously. Even there is no open-source tool or a simple MS-Excel tool that can support the application of MCDM thus far. To address this specific gap, this chapter first proposes a simple and user-friendly MS-Excel tool for four basic and popular MCDA methods – WSM, WPM, WASPAS and TOPSIS.

OVERALL COMPUTATIONAL PROCESS OF MCDA

The process of applying MCDA generally involves the following stages. The first stage is problem formulation itself, which includes the nature of decision that needs to be taken and for what purpose. Once the problem is formulated then alternative approaches or so-called options need to be identified. Let us consider the example of taking decision on buying the best smartphone within our budget, yet considering different brands and their features. In this example, the obvious options or the product alternatives are the different brands and/or models of smartphones. These alternatives will generally have their own distinctive features, advantages, and disadvantages; which we termed as attributes or criteria. Once alternatives and criteria are identified then product attribute matrix needs to be established. Generally, the products (or alternatives) are shown in rows and their criteria (features or attributes or criteria) or shown in columns. In other words, MCDA process attempts to identify the best product based on the selection criteria.

One important aspect regarding the criteria needs to be observed. Generally, the criteria will have different metrics or units and thus will be entirely different each other. In case of a smartphone, screen size, weight, appearance and cost are the common selection criteria. Though the three criteria - size, weight and cost have different units, and thus cannot be compared with each

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other. In fact, they will compete and conflict among themselves in decision making. A cheaper smartphone does not necessarily look attractive. On the other hand, the criterion of appearance does not have any metric to measure and it is a mere perception that changes from person to person. This makes it difficult to attach a value that is expected to go into product-attribute matrix. Usually a numerical value on a scale of 1 to 5 or 1 to 10 is given to each alternative based on the individual perception. For example, if a buyer feels a specific smartphone is appearing as the best then the highest value such as 5 can be attached on a scale of 5. If two different smartphones are looking at their best in the same way, both the products should/can be given the same value as 5. For this, first appropriate descriptors such best, good, above average, average, below average, worst etc., should be identified and then each of these descriptors should be given appropriate values on a certain pre-identified scale. Obviously, these are mere linguistic terms without any units as sometimes these are based on individual choices, user perceptions, likes and dislikes etc. This numerical assignment of descriptors has to be consistently applied to all of the un-measurable attributes. With this, product-attribute matrix will be filled with numerical values.

As stated earlier, attributes usually compete with each other as there will be conflict in decision making. The chief-advantage of MCDA approach is that it accommodates different nature of attributes. However, some attributes may have higher priority than others. For instance, cost may generally influence decisions in general due to obvious reasons and thus can be regarded as a prominent attribute by the users with limited budgets. It is for this reason; each attribute needs to be assigned with a certain weight depending on its prominence. For instance, if weight of the smartphone is an essential criterion for a particular prospective buyer then the attribute corresponding to the weight needs to set as higher than others. However, sum of all the weights should be unity, 1.

From the above, all the attributes finally will appear in product-attribute matrix in numerical form. However, higher value of an attribute does not necessarily mean that will be beneficial towards decision making. For example, it is better to have a higher screen size and thus for this attribute having a higher value is beneficial. On the other hand, the same will not be true for the cost attribute as higher the value of cost, it will be non-beneficial. Hence, it is for this reason, each attribute should be declared beforehand, whether it is a beneficial attribute or a non-beneficial attribute. A value of zero (0) is given to non-beneficial attribute and a value of one (1) is given to beneficial attribute. In a way, the weights will provide the required hierarchy

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of the attributes within themselves to resolve the conflict by ranking them numerically. Descriptors will determine the product ranking within a specific attribute. These two are the key aspects that makes MCDA both powerful and distinct from the classical optimization processes. Once the scaling of the non-measurable attributes, their weights and beneficial/or non-beneficial have been identified, MCDA computation can be initiated.

Since there are several MCDA approaches, each method will have its own computational process. However, normalization of product-attribute matrix is almost common to most methods and is the next step. The scope of the current discussion and the spreadsheet implementation are limited to a few selected, but prominent approaches of MCDM, which are: WSM, WPM, WASPAS (Weighted Aggregated Sum Product Assessment) and the TOPSIS. These are considered as both fundamental and powerful MCDA approaches and several articles use these methods in various areas including, but not limited to energy planning, environmental Studies and process optimization etc. As far as the technical platform for implementing is concerned, there are several choices such as C++, Java, MATLAB and even R. MATLAB would have been an ideal platform; however, the end user is expected to have the MATLAB software installed and it is a propriety software. C++ and Java are eliminated as providing graphical user interface screens for the input to the users can be little bit tricky. Then, displaying different screens with intermediate results of each method can be accomplished, however, browsing through those screens can be quite challenging for the users. On the other hand, MS-Excel is the most common and popular software as almost every uses Microsoft Office products. Naturally, there will not be any burden on the users to use the technical platform for the product itself. It should be noted that the programming within the MS-Excel requires the use of Visual Basic for Applications (VBA). Details of logic development and implementation of the code are out of scope to keep the discussion strictly focused on the applying the MCDA techniques in a straight forward manner. Since this book-chapter deals with the development of spreadsheet solution, the next section deals briefly, with the algorithms of the methods that are implemented as part of this work, for the sake of completeness so that readers do not have to refer to a different resource.

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MCDA ALGORITHMS

This section provides a brief account of the algorithms for the four MCDA methods that were implemented in the MS-Excel.

Weighted Sum Method

Step 1: Products and their attributes should be identified.
Step 2: The product attribute matrix should be completed with appropriate values. Make sure that there are no zero values to avoid unexpected results.
Step 3: identify the beneficial and non-beneficial attributes.
Step 4: Attach appropriate weightage to each beneficial and non-beneficial attribute, based on importance of the attribute or common knowledge about that attribute. Usually weightages are less than 1.
Step 5: All elements in the product attribute matrix should be normalized within the columns (or the attributes) using the equations below.

Since lower values are preferred for the elements in the columns with non-beneficial attribute, normalization is done for those columns using the equation

$$X_{ij} = \frac{Min\_value\_of\_the\_column}{X_{ij}} \tag{1}$$

Similarly, higher values are preferred for the elements in the columns with beneficial attribute, normalization is done for those columns using the equation

$$X_{ij} = \frac{X_{ij}}{Max\_value\_of\_the\_column} \tag{2}$$

After applying the above equations, the product-attribute matrix is normalized.

Step 6: Multiply every element of the normalized product attribute matrix in each column by the respective weight attached to that attribute. This results in a weighted normalized decision matrix.

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Step 7: Now add all the elements in every individual row to obtain the weighted row sum or the row wise performance score.

Step 8: Sort the rows in the descending order of the row wise performance scores. This results in the product with highest performance score (winner) being put up in the top and the product with least performance score will be put up at the end of the list.

Weighted Product Method

The weighted product method is more or similar to the weighted sum method. And thus normalization process is same. The key stages of this method are explained in the algorithm below.

Step 1: Products and their attributes should be identified.

Step 2: The product attribute matrix should be completed with appropriate values. Make sure that there are no zero values to avoid unexpected results.

Step 3: identify the beneficial and non-beneficial attributes.

Step 4: Attach appropriate, relative weightage to each beneficial and non-beneficial attribute, based on importance of the attribute or common knowledge about that attribute. Weightages are less than 1.

Step 5: All elements in the product attribute matrix should be normalized within the columns (or the attributes) using the same equations as explained in weighted sum method. After applying the equations, the product-attribute matrix is normalized just as in the previous method.

Step 6: Raise every element of the normalized product attribute matrix in each column with the respective weight attached to that attribute. This results in a weighted normalized decision matrix.

Step 7: Now multiply all the elements in every individual row to obtain the weighted row product or the **row wise performance score.**

Step 8: Sort the rows in the descending order of the row wise performance scores. This results in the product with highest performance score (winner) being put up in the top and the product with least performance score will be put up at the end of the list.

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Weighted Aggregated Sum Product Assessment (WASPAS) Method

WASPAS method is combination of WSM and WPM methods and thus depends on the results of both of these methods. Here a parameter λ, which is typically between 0 and 1. This parameter is used to assign proportionate weightage to each of the methods – WSM and WPM using the formula below

$$Q_i = \lambda Q_i^1 + \left(1 - \lambda\right) Q_i^2 \tag{3}$$

Where Q_i^1 is the performance score of the i[th] row obtained from WSM method and Q_i^2 is the performance score of the i[th] row obtained from WPM method. From the above equation it can be observed that higher the value of λ, more weightage is given to the WSM performance score. When λ is zero, first term in the WASPAS equation corresponding to the WSM method will be reduced to zero and thus giving 100% weighting to WPM performance score.

Thus, using the WASPAS equation, new performance scores are computed for each row and product rows can be sorted in the descending order of these performance scores. This results in the product with highest performance score being put up in the top and the product with least performance score will be put up at the end of the list. In other words, the product with highest performance score is highly preferred or highly ranked.

TOPSIS Method

It was first proposed in early 1980s. It is one of the popular multi-criteria decision analysis methods and widely used in several fields. This method first determines positive and negative best solutions and then ranks the different possible solutions based on the Euclidean distances from ideal best and ideal worst solutions. The overall ranking is done such a way that the chosen alternative should be very close to the ideal best (or Positive Ideal Solution (PIS)) and also it should be very far from the Ideal worst (or Negative Ideal Solution (NIS)). The algorithm for the TOPSIS method is given below:

Step 1: Products and their attributes should be identified.
Step 2: The product attribute matrix should be completed with appropriate values. Make sure that there are no zero values to avoid unexpected results.

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Step 3: identify the beneficial and non-beneficial attributes.

Step 4: Attach appropriate weightage to each beneficial and non-beneficial attribute, based on importance of the attribute or common knowledge about that attribute. Usually weightages are less than 1.

Step 5: Calculate normalized matrix by applying the equation below do all the elements of product attribute matrix. It can be observed that the denominator for all the elements in a given column is constant. As can be seen, this is a simple, linear normalization. Vector normalization is also possible for complex sets of matrix elements, but treatment of such a situation is not within the scope of present discussion. The value of the denominator is square root of sum of the squares off all the elements in that column. With this, all the elements in the product attribute matrix are normalized by common denominator that is computed by its own column. Hence this normalization preserves the nature of attribute.

$$\overline{x_{ij}} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \tag{4}$$

It should be noted that (as explained in earlier section as well) different normalization methods do exist. Paradowski et.al. (2020) has illustrated one of the such normalization techniques, which is different from the above.

Step 6: Calculate weighted normalized matrix using the equation given below. For this, multiply all the elements in the normalized matrix by the respective weights of the columns.

$$v_{ij} = \overline{x_{ij}} * w_j \tag{5}$$

Step 7: determine ideal best and ideal worst values for each column. For the columns with beneficial attribute attributes the ideal best value will be the maximum value of that respective column and minimum value of that column will be ideal worst value. Similarly, for the columns with non- beneficial attributes the ideal worst value will be the maximum of that respective column and minimum value will be the ideal best.

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Step 8: calculate the Euclidean distances between the elements of weighted normalized matrix and ideal best and ideal worst values using the equations given below.

$$s_i^+ = \sqrt{\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2} \text{ and } s_i^- = \sqrt{\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2} \quad (6)$$

Step 9: Calculate the performance score for each row or for each product using the formula given below

$$P_i = \frac{s_i^-}{s_i^+ + s_i^-} \quad (7)$$

Step 10: Determine descending order of the performance scores and rearrange the rows accordingly. In other words, the product with the highest performance score should be the first row and the product with least performance score should be the last row. This completes the ranking process through the TOPSIS method.

MS-Excel Tool for MCDM

The MS Excel tool for MCDM methods is divided into 7 sub sheets. The first and important sub-sheet is the cover page itself, which is shown in figure 3. This is the only page where users are expected to provide their inputs. The sub-sheet titled as 'weighsum' shows the computations and results of WSM method. Then then the next sub-sheet presents the computations and results of WPM. Similarly, next sub-sheets deal with WASPAS and TOPSIS methods. Final summary of results and overall rankings obtained from all of the methods are provided in the 'compare' sub-sheet, which can be considered as the overall summary and the final output. The last, but not the least, the sub-sheet named as 'cases' contains the default input data, just to provide a smooth start to a novice or first time user. The tool itself can be downloaded from the Mendeley database https://data.mendeley.com/datasets/zjckp3b259/1

The spreadsheet contains two built-in examples (Smartphone selection and Renewable energy resource selection) which are used as case studies in this book chapter and the smartphone example is displayed by default.

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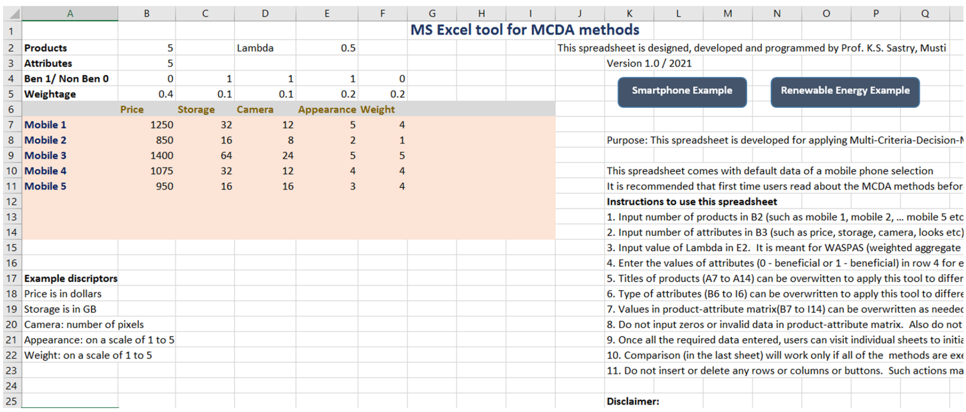
Users can click either of the buttons smartphone example or renewable energy example. Based on the action of the user, respective example will be loaded onto the cover page from the cases sub-sheet automatically. This feature provides a simple way of returning to the default data as supplied with the original sheet. However, it should be noted that accidental or deliberate overwriting of the default input data in the cases sheet can result in different set of inputs; nevertheless, the spreadsheet copies the data as it is available in the cases sheet.

Figure 3. Cover page of the MS-Excel tool that is developed as a part of this book-chapter



The overall design of this MS-Excel tool is simple, intuitive and user-friendly as it does not require any complex manipulations by the user or even deeper understanding of MCDA methods. However, for the best results; users are expected to understand the elements and features of this tool. Any mismatch like the number of products and or the number of attributes and the actual data can result in execution errors and even wrong results. For instance, this tool does not check whether the numerical values of products and attributes provided in the second and third row are matching with the number of rows and columns of the actual product attribute matrix itself. Number of products and attributes are the key variables on which the tool sets a fixed range of cells separately for the product-attribute matrix in a dedicated fashion.

Mobile 1, Mobile 2 etc., (row headings) in the first column represent different product alternatives. Column headings are the attributes for the selection criteria. These row headings, column headings and the data inside

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the matrix can be overwritten by the users as needed, when they attempt their own problems. Naturally, these all vary as per the nature of the problem and requirements. The design of the spreadsheet limits the number of products to eight and the attributes to 8 as well. Which means the maximum size of product attribute matrix can be at the most 8 by 8. Detailed instructions have been provided right on the cover page itself. Once the user formulates the problem, number of products and number of attributes should be provided in the respective cells by overwriting the existing values. parameter λ is used for WASPAS method and its default value is set to 0.5, which can be changed by the user as needed. Then the cells in the row corresponding to beneficial or non-beneficial attributes should be filled either with 0 or 1. Based on the user discretion weightages should be given. Numerical values for non-measurable attributes should be provided as described in the earlier section. The cover page also provides example descriptors and their units to assist the users. Users also can overwrite these example descriptors based on their own problem. After all the input data items are properly made available in the cover sheet then users can go into different sub-sheets to execute the different MCDA methods. Each sub-sheet has two buttons "copy data and calculate" and "clear all". The functionality of the clear all button is to clear all the existing content in that sub-sheet. When the user clicks the "copy data and calculate" button then the input data from the cover sheet is copied into the current sub-sheet and the algorithm for that respective MCDA method is executed. Intermediate steps are shown on the same sheet under the end ranking of the products is also provided. For final results and overall rankings, users are expected to visit each sub-sheet and execute the respective algorithm and obtain the results in each of those sheets. Then only the final results and overall rankings can be calculated in the 'compare' sub-sheet. In other words, the 'compare' sub-sheet merely depends on the output of the each of the MCDA methods in the respective sub-sheets. If users visit the compare sub-sheet without executing the individual methods, then overall rankings and comparisons will not be available or even if they are available they may have come from previous inputs and thus may not relate to the present set of inputs.

A few points to be noted here. There is no input field for the users on the sub-sheets for the individual methods and also users are not expected to edit any value or any cell in any of these sub-sheets. If users want to try with another set of data, then data in the cover page only needs to be changed and each of the methods should be executed in the sub-sheets for the new input. This approach presents all the information starting from the original input to

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the final result to the users in a seamless fashion so that need to sift through the sub-sheets or the cover page for the input values.

It should be noted that all the MCDA methods need not necessarily produce same output for a given, same input data set. Specifically, TOPSIS is well-known to produce different results. There are several factors that contribute to different results as each MCDA method has its own computational and search criteria in the solution space. The detailed discussion on the reasons that contribute to different outputs for the same input data sets is out of scope, as the present discussion focuses on the MS-Excel tool itself. However, the aspect of different outputs can be seen from the outputs in two cases studies here under. Readers are advised to read an interesting article "Why TOPSIS does not always give correct results?" (Bartosz et.al., 2020) for a detailed discussion on this aspect.

CASE STUDIES

Different examples have been used to illustrated MCDA methods by various authors over the years. However, this chapter uses two simple examples so that users can understand the process of using the spreadsheet quickly. The smartphone selection is a common problem and thus can be good example as many users can quickly relate to. This is due to the simplicity of the problem itself and the popularity of smartphones among wider public in any part of the world.

Case Study 1: Smartphone Selection

It is well known that smartphones are available from different brands, in too many shapes, colors and sizes and at different costs. Naturally decision making can be quite different unless users spend a lot of time in comparing the products critically. MCDA methods work very effectively when different criteria have to be applied on different products. As a first step the attributes or the criteria of selection need to be identified. Though, there are several features and attributes of the contemporary smartphones, this example considers price storage camera appearance and weight as the five different attributes. Names of the smartphones brands are avoided and instead, smartphone1, smartphone2, smartphone3 etc., for obvious reasons. Appearance and design (or looks) of a smartphone will not have any explicit units to measure. In this case users

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are expected to attach value of significance on a scale of 1 to 5 corresponding to Bad, Average, Good, Better, Best etc. One of the prominent criteria is the cost of the product for obvious reasons. Higher the cost of a product makes it less attractive for users to make a decision in its favor. Hence such attribute is considered as non-beneficial in nature. Similarly, the number of camera pixels is another attribute. Normally users prefer smartphones with higher camera pixels and thus this attribute is a beneficial one. In other words, higher values of beneficial attributes and lower values of non-beneficial attributes are strong candidates towards decision making. Comparing these attributes with one another can be a challenging task by itself. For example, it is not possible to compare appearance, cost and weight attributes of a smartphone with one another in order to make a decision.

Table 1. Default input data for smartphone selection case

Products	5				
Ben 1/ Non Ben 0	0	1	1	1	0
Weightage	0.5	0.1	0.1	0.1	0.2
	Price	**Storage**	**Camera**	**Appearance**	**Weight**
Mobile 1	1250	32	12	5	280
Mobile 2	850	16	8	2	120
Mobile 3	1400	64	24	5	350
Mobile 4	1075	32	12	3	300
Mobile 5	950	16	16	1	360

Some users may prefer lesser weight smartphones though cost may be littler higher. Some users may prefer otherwise. It is for this reason weightages are given to incorporate individual perceptions and also to set the hierarchy of the attributes among one another. Users can set their own values for these weights according to their own choices and/or preferences on the cover page of the tool. To illustrate this aspect of MCDA as well the effectiveness of the MS-Excel tool, let us consider two different data sets with varying preferences. The default input data set for the smartphone example is shown table 1, where in the weightage for the cost is set higher than other attributes. Mobile2 which has the least cost ($ 850) is ranked as the best one by all methods and overall rankings are shown in table 2

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Table 2. Overall rankings of smartphones from different MCDM

Rank	Weighted Sum	Weighted Product	WASPAS	TOPSIS
1	Mobile 2	Mobile 2	Mobile 2	Mobile 2
2	Mobile 3	Mobile 3	Mobile 3	Mobile 5
3	Mobile 4	Mobile 4	Mobile 4	Mobile 4
4	Mobile 1	Mobile 1	Mobile 1	Mobile 1
5	Mobile 5	Mobile 5	Mobile 5	Mobile 3

Now let us consider that cost is not a prominent attribute, but appearance is more important. To try this option, weighting for the cost parameter is reduced from .5 to .1, where is the weighting for appearance parameter is increased from .1 to .5. Since the tool is user-friendly, it is possible to change the data on the cover sheet and then carryout the computations in all the rests of the sheets. The changed inputs and the corresponding outputs are shown in tables 3 and 4.

Table 3. Input data with high weighting for appearance of smartphones

Products	5				
Ben 1/ Non Ben 0	0	1	1	1	0
Weightage	0.1	0.1	0.1	0.5	0.2
	Price	**Storage**	**Camera**	**Appearance**	**Weight**
Mobile 1	1250	32	12	5	280
Mobile 2	850	16	8	2	120
Mobile 3	1400	64	24	5	350
Mobile 4	1075	32	12	3	300
Mobile 5	950	16	16	1	360

And the corresponding output shows that all the methods picked mobile3 as the best, except the TOPSIS, which picked mobile2 as the best. And also it ranked mobile1 and mobile3 at the bottom. This may seem to be quite unexpected and even may seem as erroneous, but it is the way TOPSIS carries out the computations which are different from the rest of the methods. In fact, as explained earlier, this method takes the Euclidian distances into consideration from the negative and positive best values; and thus the results

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will be different from the rest. As explained earlier, this is an example to demonstrate the distinctive features of different methods and also to attest the fact that all the methods do not give same results, though same input datasets are used.

Table 4. Overall ranking of smartphones with high weighting for appearance

Rank	Weighted Sum	Weighted Product	WASPAS	TOPSIS
1	Mobile 3	Mobile 3	Mobile 3	Mobile 2
2	Mobile 1	Mobile 1	Mobile 1	Mobile 5
3	Mobile 4	Mobile 4	Mobile 4	Mobile 4
4	Mobile 2	Mobile 2	Mobile 2	Mobile 1
5	Mobile 5	Mobile 5	Mobile 5	Mobile 3

Case Study 2: Renewable Energy Selection

As of now, different renewable energies are available and each of them having their own costs, advantages and disadvantages. Social, economic and environmental impacts of renewable energies are always of significant interest to contemporary researchers. In the modern era, demand response needs to be understood well for planning the energy mix (KS Sastry, Musti, 2020b). And proportions in energy mix invariably depend on merits of different energy resources. Just as any other example, choosing a renewable energy for a specific purpose also involves both measurable and non-measurable attributes or criteria in the decision-making process. Naturally, several researchers have applied MCDA methods to renewable energy selection. This case study considers few of the well-known attributes – levelized costs of production per megawatt hour, land usage in acres, environmental friendliness and capabilities of load following. Realistic values for these parameters have been chosen from reputed references.

Both the attributes energy production costs and land usage values are measurable. Costs of energy production are obtained from Lazard (2020) and land usage values are obtained from Watts up with that? (2017). Then the rest of the two attributes are non-measurable directly. Hence, numerical values on a scale of 1 to 10 are given to both environmental friendliness and load following capabilities, based on the known information.

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Few points should be noted beforehand. This only a simple, entry level example on selecting a renewable energy resource, as the emphasis is more on using MS-Excel tool and applying the MCDA techniques. In a real world setting, there will be several different expenses in energy systems from generation point to the end use. Costs of energies vary from place to place due to local environmental conditions, sages to staff and even cost of construction etc. (Lazard, 2020). Even the costs of energies, infrastructure and technological platforms vary over the years. The default input data set for the smartphone example is shown in table 5, where in the weightage for the cost is set higher than other attributes.

Table 5. Default input data for renewable energy selection

Products	5			
Ben 1/ Non Ben 0	0	0	1	1
Weightage	0.3	0.2	0.4	0.1
	Cost	**Land Usage**	**Env. Friend.**	**Load Follow**
Solar PV	87	43.5	10	4
Wind	90	70.64	8	3
Coal	110	12.21	1	8
Natural gas	150	12.41	3	10
Nuclear	135	12.71	2	9

With the above data set, all the MCDA methods should be independently executed and the corresponding output shows that Solar PV which has the least cost ($ 87) is ranked as the best one by all methods; and there are other reasons as well including high rating given in Env. Friend. category. Solar PV which has the weightage (a beneficial criteria) is ranked as the best one by all methods and overall rankings are shown in table 6

Now let us consider that cost is not a prominent attribute, but load following ability is more important; and that the cost and land usage may not be very critical. This may be justified in a location where critical, industrial and commercial loads exist. To try this option, changes are made in such way that the attribute for the Load follow is now increased to 0.5 and the rest are reduced, while ensuring the sum of the weights of all the attributes is one. Since the tool is user-friendly, it is possible to change the data on the cover

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sheet and then carryout the computations in all the rests of the sheets. The changed inputs and the corresponding outputs are shown in tables 7 and 8.

And the corresponding output shows that all the methods identified Natural gas (also known as the Gas Peaker) as the best, except the TOPSIS which picked the Coal as the best. It also ranked Natural gas and Wind at the bottom, though weights are in favor of Env. Friend attribute. As explained earlier, it is the way TOPSIS carries out the computations based on Euclidian distances which are different from the rest of the methods; and thus the results will be different from the rest. As explained earlier, this is an example to demonstrate the distinctive features of different methods and also to attest the fact that all the methods do not give same results, though same input datasets are used.

Table 6. Overall rankings of renewable energies from different MCDM

Rank	Weighted Sum	Weighted Product	WASPAS	TOPSIS
1	Solar PV	Solar PV	Solar PV	Solar PV
2	Wind	Wind	Wind	Wind
3	Natural gas	Natural gas	Natural gas	Coal
4	Coal	Nuclear	Nuclear	Nuclear
5	Nuclear	Coal	Coal	Natural gas

Table 7. Input data with high weighting for load following capabilities

Products	5			
Ben 1/ Non Ben 0	0	0	1	1
Weightage	0.1	0.2	0.2	0.5
	Cost	**Land Usage**	**Env. Friend.**	**Load Follow**
Solar PV	87	43.5	8	3
Wind	90	70.64	8	3
Coal	110	12.21	1	8
Natural gas	150	12.41	3	10
Nuclear	135	12.71	2	9

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Table 8. Overall ranking with high weighting for load following capabilities

Rank	Weighted Sum	Weighted Product	WASPAS	TOPSIS
1	Natural gas	Natural gas	Natural gas	Coal
2	Nuclear	Nuclear	Nuclear	Solar PV
3	Coal	Coal	Coal	Nuclear
4	Solar PV	Solar PV	Solar PV	Natural gas
5	Wind	Wind	Wind	Wind

DISCUSSION AND PROSPECTS FOR FURTHER WORK

From the above sections, it can be seen that the developed MS-Excel is functional in its scope and meets the set objectives. However, there are a lot of MCDA techniques, but there is no single software that deals with all the methods is not yet available. Given the vastness of MCDA techniques, designing a MS-Excel tool with different methods can be complex as well. Not all methods can function with same input as well. Process of defining inputs also varies and some of the methods such as AHP and TOPSIS can also be used to identify and/or adjust the weights with or without fuzzy techniques. Then there exist different normalization techniques as well. There is no guarantee that all the methods produce same output, but it is always thought-provoking to understand why and when different outputs get generated. As far as the application of MCDA to energy systems, finding a suitable method to a specific problem can be challenging. Abu & Daim, (2013) aptly puts as

The use of multi-criteria decision analysis (MCDA) techniques provides a reliable methodology to rank alternative renewable energy resources, technologies and projects in the presence of different objectives and limitations. Even with the large number of available MCDA methods, none of them is considered the best for all kinds of decision-making situations. Different methods often produce different results even when applied to the same problem using same data. There is no better or worse method but only a technique that fits better in a certain situation. The current research does not give a clear view about the trend in literature, but can give an insight about the direction it is going.

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It is for this reason, a suitable computational tool such as the one developed as a part of this work can provide researchers a chance to apply different methods with same input and then observe the output. Thus, it can be understood that this tool itself needs a lot more features including – adding new MCDA methods, sensitivity analysis etc.

CONCLUSION

An MS-Excel tool for applying four different MCDA techniques WSM, WPM, WASPAS and TOPSIS has been proposed, developed and is made available on Mendeley data repository for all to download without any payment. Motivation for the developing this tool is derived from the fact that there is no such tool presently available. To this effect, required literature review specifically on applying MCDA methods to energy systems has been incorporated. Two different case studies with varying input datasets have been used to demonstrate the effectiveness of developed tool.

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Chapter 4
Design and Development of a Hybrid DC-DC Converter for Solar-Battery-Based Standalone Milk Vending Machine

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ABSTRACT

Dairying has become a major secondary source of income for several rural families. The easily perishable nature of milk increases the spoilage of the product and reduces the dairy farms' productivity in rural areas due to power supply shortage issues. In order to overcome the inaccessibility of proper preservation strategies, this chapter proposed a hybrid DC-DC converter for a solar battery-powered milk vending machine. This proposed system can work continuously and provides an uninterrupted power supply to maintain the milk quality at an optimum level. Moreover, the proposed system utilized a novel converter to reduce the number of power conversion stages and compact

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the system. Besides, the proposed converter can achieve a higher gain ratio with fewer components. Furthermore, a proper algorithmic-based control scheme has been implemented to maintain effective power flow management. Finally, to verify the feasibility and performance of the system, detailed results are obtained at different dynamic conditions, and various case studies are presented in this chapter.

INTRODUCTION

India ranks first among the world's milk-producing Nations since 1998. Inaccessibility of proper preservation strategies of milk due to shortage of power supply is one of the challenging issues faced by dairy farmers. Proper refrigeration at 40°F (4°C) can extend the longevity of milk to 5-7 days, which is otherwise perishable within 2 hrs (Iqbal et al., 2018). Many dairy farmers and processors may lose significant earning potential due to the shortage of power supply in rural areas. The momentousness of renewable energy resources is accelerating rapidly in the last few years. Among all renewable resources, solar power is the cleanest form of energy and is modular and scalable. In remote areas, solar PV is the primary choice where substantial power line construction may find solar PV more cost-effective. Due to the intermittent nature of energy from solar PV, it is required to integrate energy storage systems for the stable operation of the standalone PV system. Solar-battery powered milk vending machine is an efficient way of storing and distributing milk in rural areas with considerable solar radiation (Anand et al., 2018; Liu & Li, 2006). Solar-battery powered milk vending machine is an efficient way of storing and distributing milk most hygienically and ecologically. This clean energy solution increases small-scale dairy farmer's productivity and income by significantly decreasing milk spoilage.

In order to assure the continuous operation of standalone photovoltaic systems, the conventional way of power converters with batteries are mandatory (Tao et al., 2008). Multi-port converter technologies have gained so much importance over few years due to limited required components, high power density, and high-efficiency characteristics. A multi-port converter is expected to offer direct integration of energy input sources, storages, and the load.(Wu et al., 2012)-(Wu et al., 2014). Multi-port converter topologies can be classified into non-isolated, partially-isolated, and fully-isolated. It can operate in boost, buck, and buck-boost and the bidirectional way (Zhu, Zhang, Zhang et al,

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2015)-(Zhao et al.,). Several researchers have been published various articles in the field of isolated dc-dc converters for simultaneous power management of multiple energy sources. An isolated dc-dc converter is extensively utilized in the power management operation of solar PV, battery and load.

These converter interface sources of different voltage-current characteristics; therefore, the soft switching approach is required for the main switch using LCL resonant circuit (Zeng et al., 2015). Three-port dc-dc converter is proposed in (Bastidas-Rodriguez et al., 2014). It has capable of interfacing PV port, battery port, and load port. Similar to previous work, the soft-switching operation is mandatory. Therefore, ZCS operation has been achieved, which improves the efficiency. Also, with the help of battery management command, the PV generation power, load power demand is working in MPPT mode and conductance mode effectively. Flux additivity-based multi-input converter has been proposed in (Krishna et al., 2021). Instead of electrical, magnetic form is used for the integration of input sources. Isolated converters can offer better safety with a high step-up ratio. However, it tends to be more expensive, and the additional components make it bulky. Thus, the efficiency and regulation of non-isolated converters tend to be better than that of an isolated converter. Three port high gain non-isolated dc-dc converters proposed in (Li & Shi, 2019) can simultaneously act as a high gain converter and as a multi-port converter. To obtain high voltage gain, it uses coupled inductor technique. However, it requires many semiconductor devices in the coupled inductor, which makes the circuit bulky and costly. Moreover, based on the power availability, only two modes of operation are possible and validated.

A single switch three-port dc-dc converter for a standalone PV-battery power system is introduced (Bhaskar, Sanjeevikumar, Holm-Nielsen et al, 2019). Here, the switches in the conventional cascade converter are substituted with one switch with two diodes. In this design, the challenging part is that the converter in two stages needs to operate synchronously to achieve single switching and is suitable for floating type loads. A power flow management system for solar PV-battery-backed standalone system is proposed in (Bhaskar, Al-Ammari, Meraj et al, 2019). A time-sharing voltage-mode control scheme has been utilized to maintain constant dc load voltage and to extract maximum solar PV. The converter is capable of operating in surplus and deficit PV power. Here, they failed to discuss all the possible operating conditions depending upon the available solar PV power. There are various researches introducing dc-dc converters with high voltage conversion ratio (Mizard et al., 2019)-(Ravi et al., 2020).

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To extract maximum power from solar PV and improve the overall system efficiency, a maximum power point tracking algorithm is an effective way to implement standalone PV systems (Ravi et al., 2011). MPPT controllers are highly important to ensure the system operating at optimum conditions (Duryea et al., 1999)-(Madichetty et al., 2019). A standalone BLDC based solar air cooler with an MPPT tracking system is proposed (Teja et al., 2016), and it comprises of PV array, DC-DC boost converter and DC-DC buck converter. The proposed integrated three-port converter (Jiang & Fahimi, 2011) and B4-inverter fed BLDC drive is targeting low or medium applications.

In order to overcome the drawbacks discussed in these articles, this particular chapter proposes a novel hybrid dc-dc converter with the integration of solar PV, battery, grid, and the BLDC motor Load for the standalone Milk Vending Machine. This research aims to design and develop a hybrid dc-dc converter for the solar-battery powered uninterrupted milk vending machine, which can work continuously as a standalone system and provide an uninterrupted power supply to maintain the quality of the milk. The proposed converter with a proper energy/storage management system can provide an uninterrupted power supply to the BLDC Motor load by trying to maintain constant dc-link voltage. During surplus PV power, the batteries store the excess energy, and during a deficit of PV power, both solar PV and battery meet the energy demand. In rainy seasons or during non-sunny hours, the battery can be alone able to supply the power to load. When both solar PV and battery are not available during continuous rainy periods, the grid comes into active mode to supply the power into BLDC Motor load. The main contributions of the proposed technical work presented in this chapter are:

1. The proposed hybrid DC-DC converter reduces the power conversion stages by integrating input sources, energy storage, and the load.
2. The overall arrangement makes the system more compact by utilizing fewer components.
3. The introduced hybrid DC-DC converter is designed to achieve a high gain ratio.

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PROPOSED SOLAR-BATTERY BASED MILK-VENDING MACHINE

The generalized block diagram of the proposed hybrid dc-dc converter with solar PV, battery, and BLDC Motor is illustrated in Fig.1. The proposed research consists of a solar array-powered hybrid DC-DC converter, ampere-hour powered battery, and BLDC motor drive with an effective energy management system to take care of excess, deficit, and extremely worst PV power availability. BLDC is the suitable choice of motor for reciprocating compressors in refrigerators. Low maintenance costs and less frequent maintenance requirements make the BLDC motor is more attractive than other DC motors. It is compact in size, having better speed control, provides high torque and efficiency. By sensing the internal and external temperature of the system, the thermostat controls the cooling process by switching the compressor on and off. The proposed hybrid dc-dc converter acts as an interface between the input sources and the BLDC motor drive. Solar PV with MPPT control and battery storage system is connected to the hybrid converter. The battery storage unit is integrated with the plan to perform power exchange according to the input solar insolation and temperature. For better understanding, there are different cases have been discussed in this chapter. During sunny hours, solar PV power is more than the load demand. Power is distributed among the load and the battery. When solar power is just sufficient to meet the load demand, the battery is isolated from the circuit. During non-sunny hours, the power deficit can be met by the battery storage system. In extreme cases, when solar PV and battery storage are not available, there is a provision to supply power from the ac grid through a rectifier. Under this mode, active rectification mode comes into the picture. Apart from this, to assure the quality of milk, a simple refrigeration unit is required based on a compressor, evaporator, and condenser. The liquid refrigerant in the compressor is compressed and turned into hot gas, and pushed to the condenser. Then by absorbing some of the heat, it turns into liquid. It proceeds to the expansion valve, where it expands by losing heat and pressure. Refrigerant is then piped into an evaporator where the cooling of load inside the refrigerator takes place as a result of the exchange of heat. The gas is again pushed back to the compressor, and the cycle starts again.

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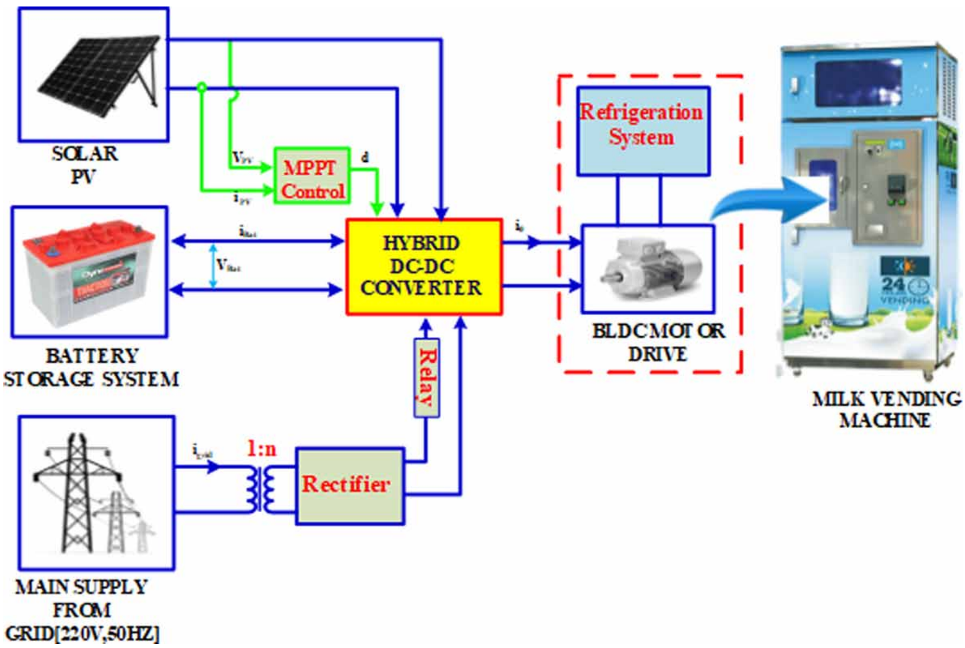
Figure 1. Generalized block diagram of the proposed system for standalone milk vending machine



Novel Hybrid DC-DC Converter

The proposed topological structure of hybrid DC-DC converter is shown in Fig. 2: The converter comprises of four power–controlled switches ($S_{1,}$ S_2, $S_{3,}$ and S_4), three uncontrolled switches $D_{1,}$ $D_{2,}$ and $D_{3,}$ and antiparallel diodes of MOSFET's, three inductors ($L_{1,}$ L_2, L_3), and two capacitors (C_1 and C_2) and a BLDC motor load. The solar PV is connected to Port-1, and the load is connected to Port-3. The converter consists of two unidirectional ports (port-1 and port-3) and one bi-directional port (port-2). According to the availability of solar radiation and the temperature changes, the DC-DC converter plays a crucial role in changing the operation in different modes. The power flow among the input sources and the output is balanced by maintaining constant dc-link voltage across the capacitor C_1. The biggest challenging task is to maintain the dc-link voltage under all operating conditions. The solar PV, along with the battery storage system, assures continuous operation of the standalone system. There is a provision for supplying power from 220 V, 50 Hz AC grid through a rectifier in extremely worst scenarios. The main

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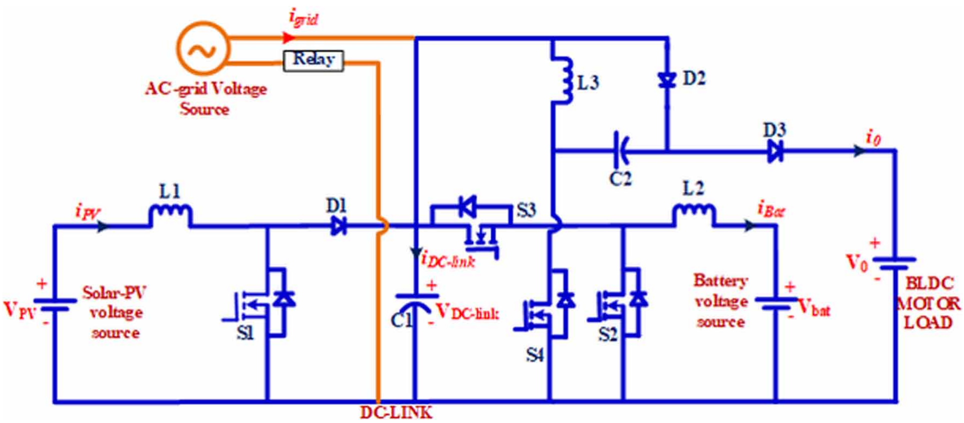
elements of L_3, D_2, C_2, and S_4 enhance the voltage conversion capability and the power flow.

Figure 2. Novel hybrid DC-DC converter



The different modes of operation of the dc-dc converter with their switching states, equivalent circuit diagrams, and steady-state waveforms are explained in this section. In Table. I, the modes of operation of the converter, have been provided with the proper switching sequence.

Table 1. Summary of modes of operation for proposed hybrid DC-DC converter

	PV to Battery+Load		**PV+Battery to Load**		**PV to Load**		**Battery to Load**	
	Mode 1	**Mode 2**	**Mode 3**	**Mode 4**	**Mode 5**	**Mode 6**	**Mode 7**	**Mode 8**
S_1	ON	OFF	OFF	ON	ON	OFF	ON	ON
S_2	OFF	ON	ON	OFF	OFF	OFF	ON	OFF
S_3	ON	OFF	OFF	ON	OFF	OFF	OFF	ON
S_4	ON	OFF	OFF	ON	ON	OFF	OFF	ON
D_1	OFF	ON	ON	OFF	OFF	ON	OFF	OFF
D_2	ON	OFF	OFF	ON	ON	OFF	OFF	ON
D_3	OFF	ON	ON	OFF	OFF	ON	ON	OFF

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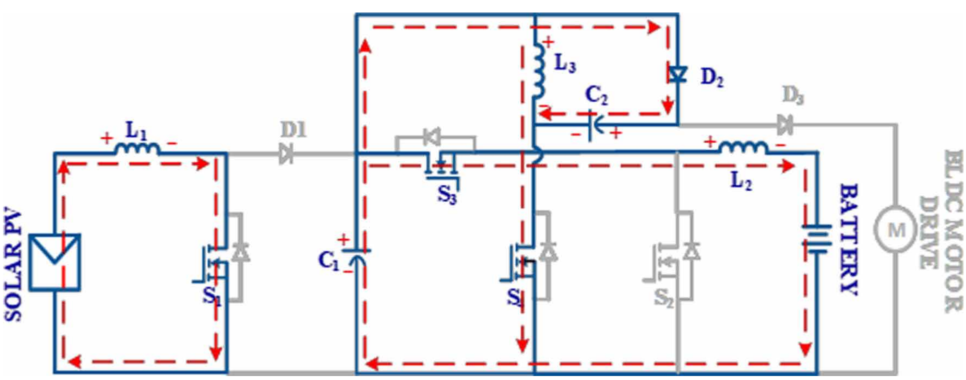
Case – I (PV to Battery and Load)

In this case, when there is an excess power generation from solar PV, then the solar PV can supply the power to load and as well as stores the remaining power into the battery. The power flow from the source to load is maintained by controlling the switches (S_1, S_2, $S_{3,}$ and $S_{4)}$ turned ON and OFF. Thus, it can be elaborated these operations into two modes.

Mode-1

The switches S_1, S_4, S_3 are turned ON, and S_2 is turned off (duty cycle for mode-1is DT). When the switch S_1 is turned ON, inductor L_1 is magnetized by input supply (V_{pv}). In this mode, the voltage across capacitor C_1 (dc-link voltage) is higher than the reference voltage. When S_3 is ON, inductor L_2 gets charged through the battery. When switch S_4 is turned ON, inductor L_3 is charged through C1-L3-S4, and the capacitor C2 is also charged through the path C_1-D_2-C_2 S_4 and D_1. D_3 are reversed biased, and diode D_2 is forward biased. The equivalent circuit of the proposed converter working in this mode is shown in Figure 3. The polarity of the voltage that appears across the inductors is also represented in the equivalent circuit.

Figure 3. Mode -1 equivalent circuit of the proposed converter



$$V_{L1} = V_{PV} \quad (1)$$

$$V_{L2} = V_{C1} - \mathrm{V}_{\mathrm{Bat}} \quad (2)$$

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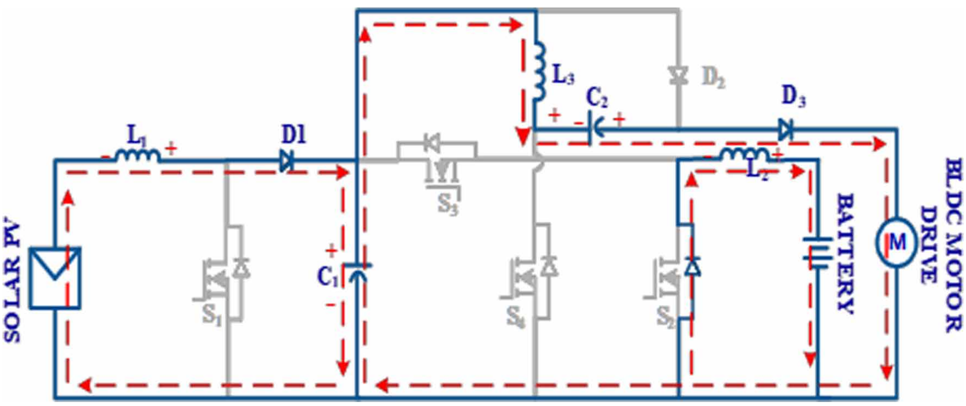
$$V_{L3} = V_{C1} \tag{3}$$

$$V_{C1} = V_{C2} \tag{4}$$

Mode-2

The switches S_2 are turned ON, and S_1, S_4, S_3 are turned off (duty cycle for mode- 2 is ((1- d) T). When switch S_1 is turned off, diode D_1 is forward biased, and inductor L_1 is demagnetized to charge the capacitor C_1. When S_4 is OFF, energy stored in the inductor L_3 and capacitor C_2 are released their energy to the load through the current path of C_1 - L_3 – C_2 - D_3 - LOAD. Since switch S_3 is turned OFF, inductor L_2 is demagnetized in series with the battery, and the battery starts to charge through the antiparallel diode of switch S_2. The equivalent circuit shows the power flow as shown in Figure 4.

Figure 4. Mode -2 equivalent circuit of the proposed converter



The inductor voltage expressions for the corresponding modes can be written as follows,

$$V_{L1} = V_{PV} - V_{C1} \tag{5}$$

$$V_{L2} = -V_{Bat} \tag{6}$$

$$V_{L3} = V_{C1} + V_{C2} - V_{Bldc} \tag{7}$$

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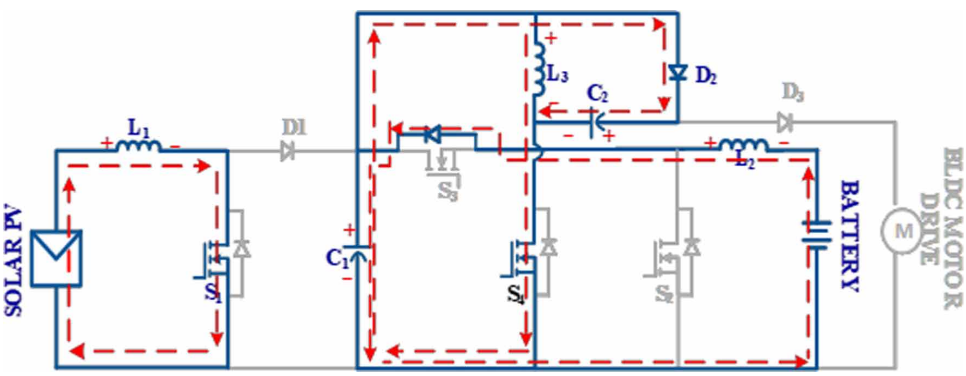
Case – II (PV and Battery to Load)

If the solar PV available is not sufficient to feed the load, then in order to meet the load demand, the remaining energy is supplied from the battery. In this case, the dc-link voltage is lesser than the reference voltage. Here, the proper power flow can be maintained by controlling the switches (S_1, S_2, S_3, and S_4). Depending on the switching states, this mode can be divided into sub-states.

Mode-3

When the switch S_1 is ON, inductor L_1 begins to charge from Solar PV. By turning ON switch S_4, the charge stored in capacitor C_1 begins to discharge to magnetize inductor L_3 through the path C_1-L_3-S_4 and to charge the capacitor C_2 through C_1-D_2-C_2-S_4. The charge stored in inductor L_2 is demagnetized to charge the capacitor C_1 through the antiparallel diode of switch S_3. The equivalent circuit diagram for this state is clearly represented in Figure 5.

Figure 5. Mode -3 equivalent circuit of the proposed converter



The voltage expressions of this particular mode has been written here.

$$V_{L1} = V_{PV} - V_{C1} \tag{8}$$

$$V_{L2} = -V_{Bat} \tag{9}$$

$$V_{L3} = V_{C1} + V_{C2} - V_{Bldc} \tag{10}$$

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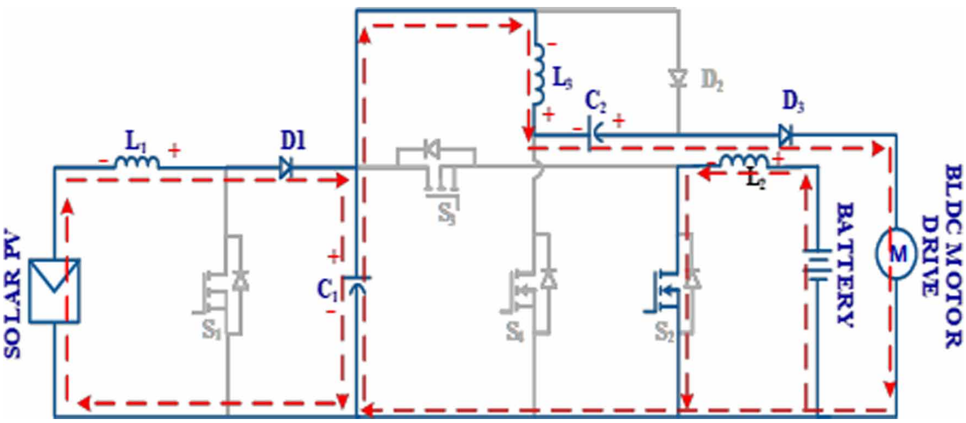
Mode-4

In this state, the switches S_1, S_3, S_4 are turned OFF, and switch S_2 is turned ON. When S_1 is OFF, inductor L_1 is demagnetized to charge the capacitor C_1 through D_1. The energy stored in L_3 and C_2 is discharged to supply the load through the path C_1-L_3-C_2-D_3-LOAD. The inductor L_2 is gets magnetized by battery voltage through the switch S_2. The equivalent circuit and the inductor voltage equations corresponding to this mode are shown in Figure 6.

Figure 6. Mode-4 equivalent circuit of the proposed converter



$$V_{L1} = V_{PV} \tag{11}$$

$$V_{L2} = V_{C1} - V_{Bat} \tag{12}$$

$$V_{L3} = V_{C1} \tag{13}$$

Case – III (PV to Load)

The PV power is completely directed to the load when the PV power generation is approximately equal to the load requirement. In this state, the battery can be completely isolated by turning off both S_2 and S_3 switches. There is no power exchange that takes place between the battery and dc-link voltage. In this case, the dc-link voltage is approximately equal to the reference voltage. Switches

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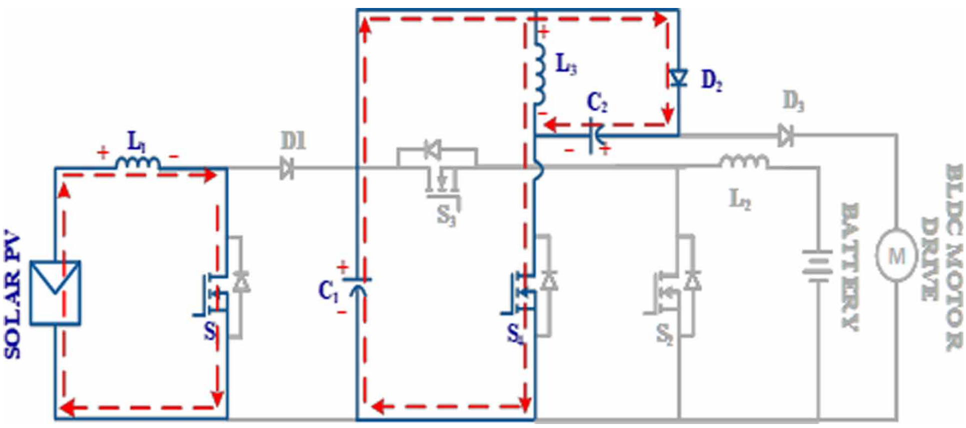
S1 and S4 can control the power flow from solar PV to load. Depending on the switching states, this can be divided into two modes.

Mode-5

When the switch S_1 is ON, inductor L_1 begins to charge from solar PV. Inductor L_3 and capacitor C_2 start to charge from capacitor C_1 by turning ON the switch S_4 through the path C_1-L_3-S_4 and C_1-D_2-C_2 $S_{4,}$ respectively. The equivalent circuit of the proposed converter during this mode can be represented by the given Figure 7. The corresponding inductor voltage equations are also expressed below.

Figure 7. Mode-5 equivalent circuit of the proposed converter



$$V_{L3} = V_{C1} \tag{14}$$

$$V_{L3} = V_{C1} \tag{15}$$

$$V_{C1} = V_{C2} \tag{16}$$

Mode-6

In this mode, both switches S_1 and $S_{4,}$ are turned OFF. The inductor L_1 discharges through the capacitor $C_{1,}$ where inductor L_3 and C_2 discharge the stored energy to supply the load demand through the path C_1-L_3-C_2-D_3-LOAD.

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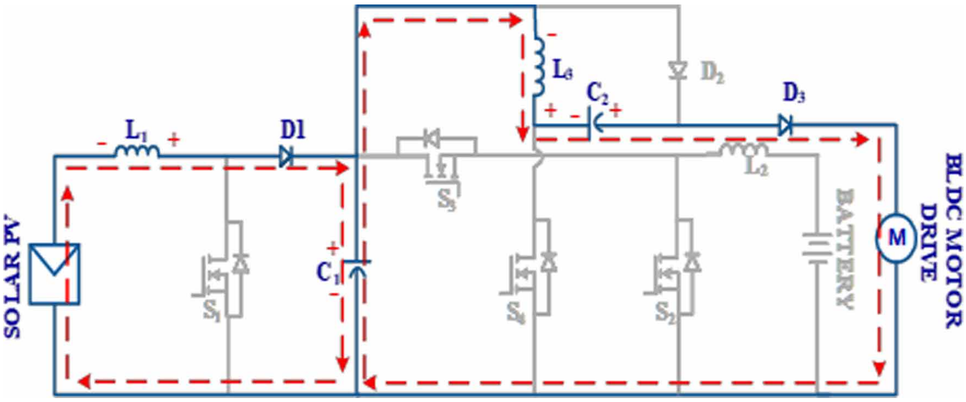
The corresponding equivalent circuit with power flow and voltage equations are presented in Figure 8.

Figure 8. Mode-6 equivalent circuit of the proposed converter



$$V_{L1} = V_{PV} - V_{C1} \tag{17}$$

$$V_{L3} = V_{C1} + V_{C2} - V_{Bldc} \tag{18}$$

Case – IV (Battery to Load)

During the absence of solar PV power, the battery supplies the energy to load and ensures the system's continuous operation. The power flow from the battery to load can be controlled by switches S_2, $S_{3,}$ and S_4. According to the switching states, this can be divided into two separate states.

Mode-7

When S_4 is ON, inductor L_3 is gets charged through C_1-L_3-S_4. Simultaneously, the capacitor C_2 is also gets charged through the path C_1-D_2-C_2 $S_{4.}$ The energy stored in the inductor L_2 is demagnetized to charge the capacitor C_1 through the antiparallel diode of switch $S_{3.}$ The equivalent circuit is shown in Figure 9, and voltage expressions are given here,

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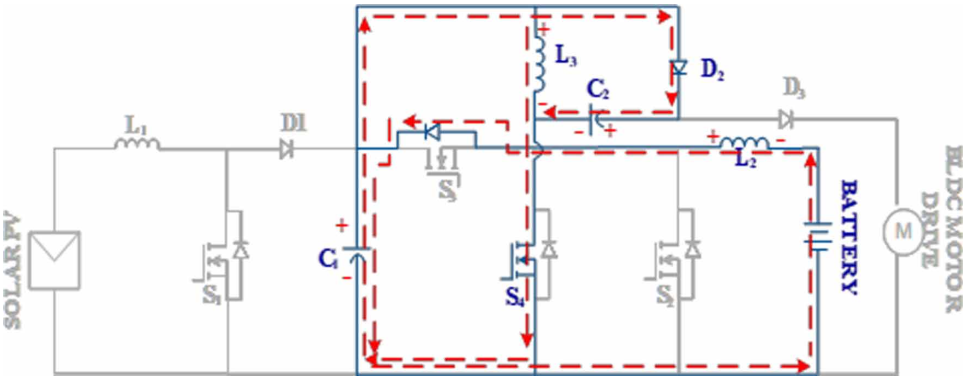
Figure 9. Mode -7 equivalent circuit of the proposed converter



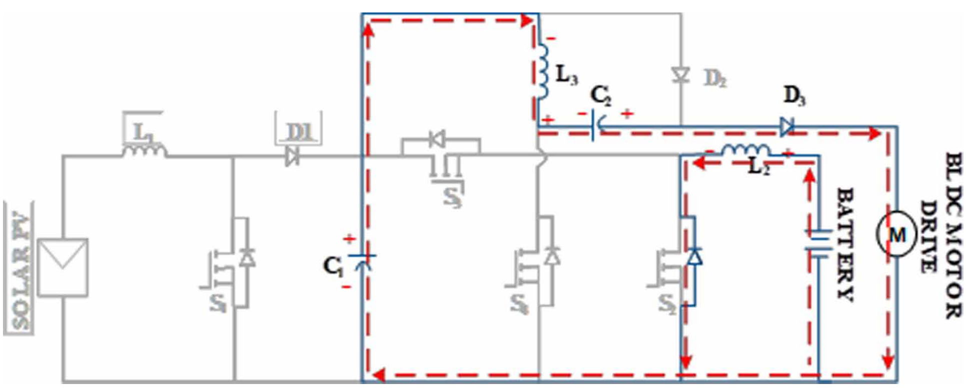
$$V_{L2} = -V_{Bat} \quad (19)$$

$$V_{L3} = V_{C1} + V_{C2} - V_{Bldc} \quad (20)$$

Mode-8

When S_4 is OFF, inductor L_3 and capacitor C_2 supply the stored energy to the load through the path C_1-L_3-C_2-D_3-LOAD. By turning ON switch S_2, inductor L_2 is gets charged from the battery source. The operation is represented in an equivalent circuit, as shown in Figure 10.

Figure 10. Mode-8 equivalent circuit of the proposed converter



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$$V_{L3} = V_{C1} + V_{C2} - V_{Bldc} \tag{21}$$

$$V_{L3} = V_{C1} \tag{22}$$

The different switching actions and the corresponding voltage and current waveforms of inductors (L_1, L_2 and L_3) and capacitors are represented in Fig 4. The theoretical waveforms are obtained by analysing the charging and discharging operation of the inductors and capacitors during different cases.

According to volt-second principle, the expression can be written as,

$$V_{PV}.DT + \left(V_{PV} - V_{C_1}\right)\left(1-D\right)T = 0 \tag{23}$$

$$\left(V_{C1} - V_{Bat}\right)DT + V_{Bat}\left(1-D\right)T = 0 \tag{24}$$

$$V_{C1}.DT + \left(V_{Bldc} - V_{C1} - V_{C2}\right)\left(1-D\right)T = 0 \tag{25}$$

After simplifying the above equations, the voltage gain ratio of the proposed hybrid converter can be obtained as,

$$\frac{V_{Bat}}{V_{PV}} = \frac{D}{1-D} \tag{26}$$

$$\frac{V_{Bldc}}{V_{PV}} = \frac{2-D}{\left(1-D\right)^2} \tag{27}$$

$$\frac{V_{Bldc}}{V_{Bat}} = \frac{2-D}{\left(1-D\right)^2} \tag{28}$$

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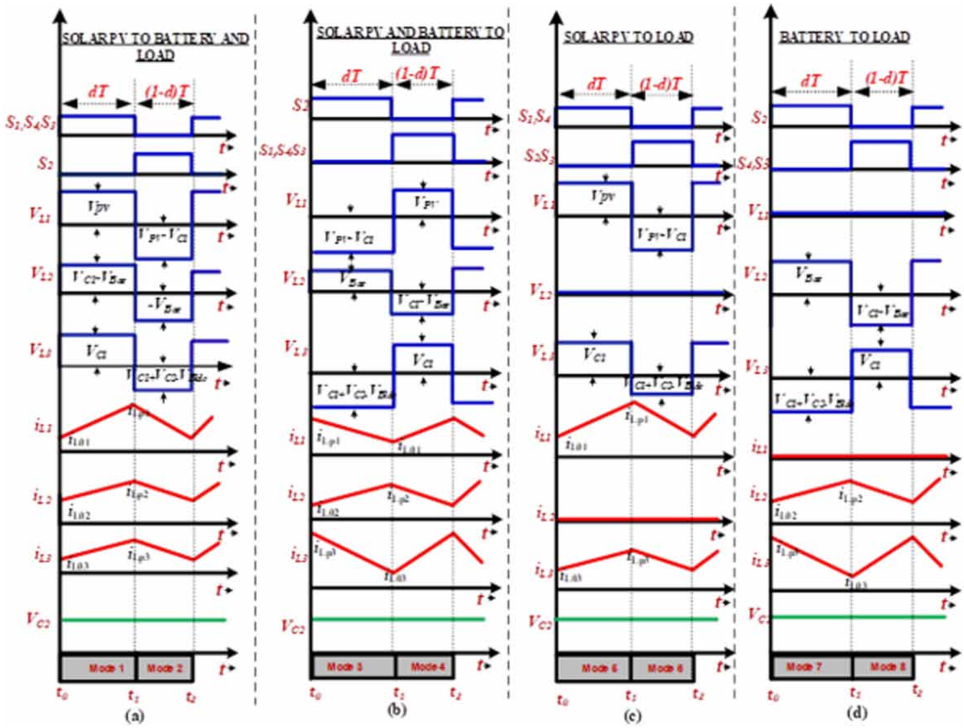
Figure 11. Theoretical waveforms for a proposed converter (a) case1-solar PV to battery and load (b) case2-solar PV and battery to load (c) case3-solar PV to load (d)case4-Battery to load



POWER MANAGEMENT OF THE PROPOSED CONVERTER

A proper algorithmic-based control scheme was designed to achieve effective power flow from the input sources to load, duty cycle selection, modes of operation, and battery energy management. Based on the availability of solar PV power, SOC of battery and load demand a proper selection of mode of operation and the required switching signals are made (Chen et al., 2012). In order to maintain constant output voltage, here a simple voltage control method is utilized. An error signal is generated by comparing output voltage and the reference voltage and then is compared with the fixed frequency sawtooth signal to find the duty ratio. There are mainly four working scenarios that can be explained as per the availability of solar power.

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Scenario 1 (P_{PV} >P_{Load}): Solar power available is more than the load demand. The proposed converter works in MPPT mode by controlling switch S_1. By controlling the switch, the S_3 battery can charge by working it as a buck converter, and the excess energy is stored in the battery. Hence, the battery is charged, and the dc-link voltage is maintained in a set boundary region.

Scenario 2 (0<P_{PV} <P_{Load}): When solar power is not sufficient to supply the load with the help of the MPPT algorithm. Then to meet the load demand, the battery is discharged by controlling switch S_2. Thus, the dc-link voltage is maintained in a set boundary region.

Scenario 3 (P_{PV} = P_{Load}): Solar power is just sufficient to meet the load demand. Thus, PV power is only able to supply the power to load.

Scenario 4 (P_{PV} = 0): When no solar PV power is available, then the battery is discharged to meet the load demand.

Scenario 5 (P_{PV} = 0, P_{Bat} =0): Both solar PV and Battery is not available, then the AC grid supplies the power through a rectifier to meet the load. 220 V AC main is connected through a rectifier to supply power to load.

Algorithmic-Based Control of the Proposed System

The flowchart of the proposed power flow algorithmic approach is represented in Fig. 5. There are four major cases of operation depending upon the PV power availability and the dc-link voltage. The main four cases have been discussed as follows.

Case 1

In solar PV hours, when the solar PV power available is more than the load demand, dc-link voltage across the capacitor C_1 is higher than the reference voltage, which is proportional to excess power generation. In order to enhance the life of the battery, the excess power generated can be delivered to the battery storage unit only after checking the SoC level of the battery.

SoC < H

If the SoC of the battery is less than the maximum value, then the excess power ($P_{Bat} = P_{PV} - P_{Load}$) is stored in the battery. Then the P_{Bat_ref} value is updated by checking the $V_{dc\_err} = V_{dc\_linkref} - V_{dc\_link}$.

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SOC > H

If SoC is higher than the maximum set limit, the battery is unable to accept the excess power. Thus, MPPT mode is turned OFF so that the load gets the power from only solar PV.

Case 2

During lower solar isolation levels, the solar PV power availability is less than the load. Therefore, the V_{dc_link} value is higher than the $V_{dc\_linkref}$ value, which is also proportional to deficit power availability. To ensure the system's continuous operation, the remaining power of the load is compensated by the power from either battery or AC grid by checking the conditions. There are two condition needs to checked before executing the operation.

SoC < L

If the SoC level of the battery is less than the minimum set limit, the battery cannot supply the power required to meet the load demand. Therefore, the battery storage unit is disconnected from the system. The AC grid connected to the circuit is enabled by turning ON the relay. Finally, the 220 V main supply from the AC grid is stepped down, and then dc voltage is generated from the full-wave bridge rectifier. Then the smooth dc voltage is fed to the hybrid converter to meet the load.

SoC > L

When the SoC level is higher than the minimum set value, the battery storage unit feeds the power required to meet the load. The P_{Bat_ref} value is updated till the V_{dc_err} value becomes zero. The power required by the load is automatically consumed from the battery to satisfy the load. Hence, the power is being balanced under this mode.

Case 3

When the value of V_{dc_link} voltage is equal to the $V_{dc\_linkref}$ voltage, load demand is met by solar PV alone if the power produced is just sufficient to meet the load demand. If there is any power deficit that occurs, the battery begins to

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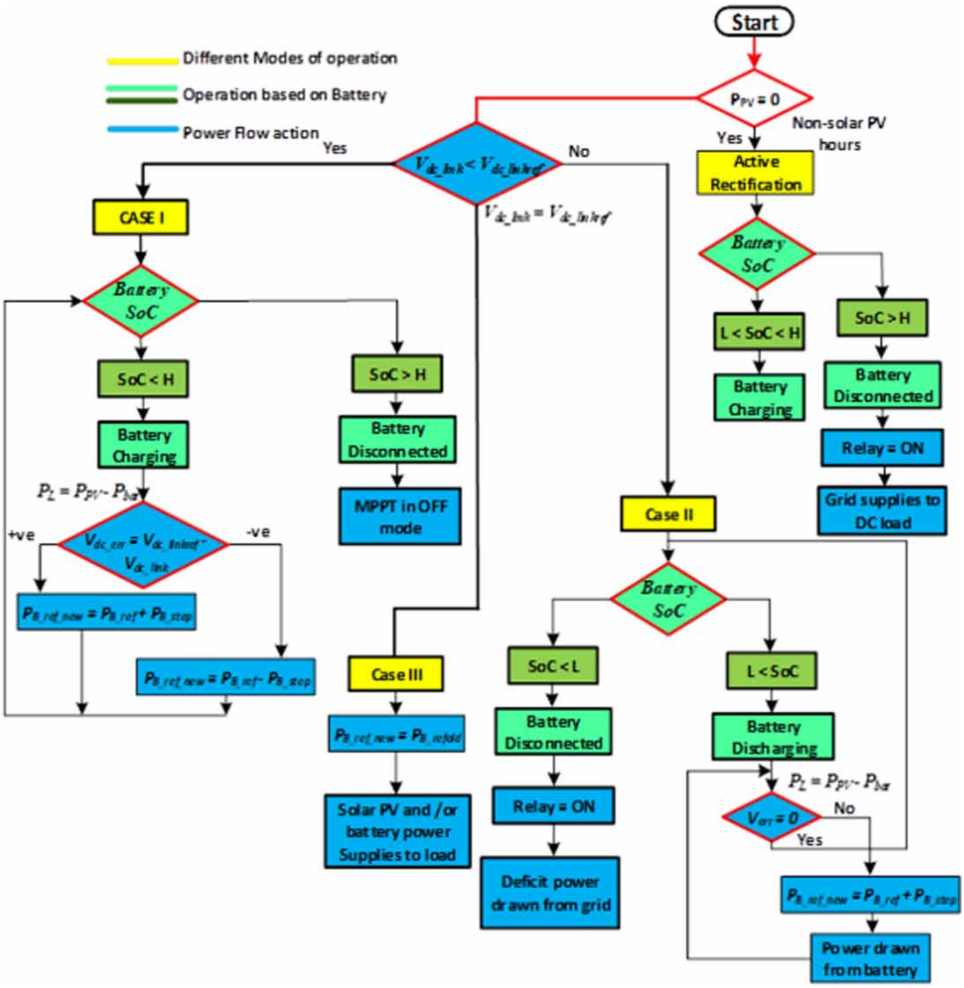
discharge. Thus, the system's continuous operation is ensured by supplying power from solar PV and/or battery.

Figure 12. Flow chart of power flow algorithm



Case 4

During non-solar PV hours ($P_{PV} = 0$), the system's continuous operation can be ensured by supplying the power from the AC grid. The 220 V main is stepped down into considerable value, and then dc voltage is generated from

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the full-wave bridge rectifier. Therefore, the smooth dc voltage is fed to the hybrid converter to satisfy the load.

L < SoC < H

When the SoC level of the battery is less than the maximum value, load power is met by the power from the AC grid, and also, the battery gets charged. Thereby, battery power can be used to compensate the load power under any power deficit conditions.

SoC > H

If the SoC level of the battery is higher than the maximum value, the battery is disconnected since it is already in its optimum state. Then the load power is met by power from the AC grid after the rectification process.

MPPT Controller for PV Panel

Depending upon the orientation of the solar field, seasons, and geographical latitude solar irradiation changes, PV power availability also varies. Energy generated by photovoltaic cells depends on irradiation and temperature. In order to transfer the maximum amount of power to the load, it is necessary to identify the particular point on the solar PV V-I characteristic. According to the change in climatic or environmental conditions, the maximum power point keeps shifting its position. In order to keep tracking maximum power point, MPPT controllers have become an essential part of the solar PV system. Among several MPPT algorithms, perturb and observe (P&O) MPPT algorithm is one of the most preferred methods due to its simple control and easier implementation. P&O method involves a perturbation in the operating voltage of the PV array as per the change in power. If the induced changes increase the power output, then there is an incremental in the operating conditions of duty ratios in the same direction. The operation gets reversed if there is a decrement in the change in power. The P&O flow diagram of the MPPT technique is illustrated in Figure 13.

The process is periodically repeated until the maximum power point is obtained. The perturbation duty cycle at the time (s+1) is represented in below equation ():

$$d(s+1) = d(s) + 2(sign - 1)D \tag{29}$$

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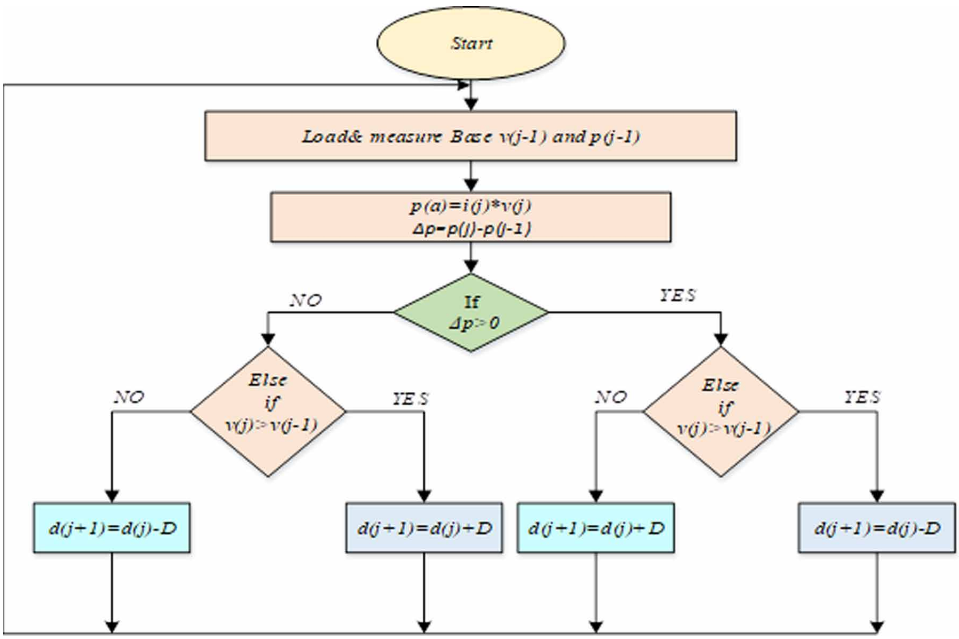
Where *sign* is

$$sign = \left[P_{PV}(S) - P_{PV}(S-1)\right] > 0 \oplus \left[v_{PV}(S) - v_{PV}(S-1)\right] > 0 \tag{30}$$

Here the power and voltage drawn from PV is represented as P_{PV} and V_{PV}.

Figure 13. P&O algorithm flowchart



Battery Charging and Discharging Control

To ensure continuous operation of the standalone system along with solar PV array battery pack is also required. During the surplus of solar energy, the excess energy can be stored in the battery pack, and whenever there is a deficit of solar energy occurs, the energy from the battery can meet the load (Wang & Li, 2013). In standalone PV applications, commonly used rechargeable batteries are lead-acid batteries and lithium-ion batteries. Considering the roundtrip efficiency and effectives of the operation, a lithium-ion battery is used in this proposed system. The battery is coupled with the dc-link capacitor, and switches S_3, S_2 is utilized for charging and discharging, respectively. Here

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the energy flow is possible in both directions, i.e., from the battery and to the battery.

In non-solar PV hours, the 220 V main supplies from the AC grid is connected with the circuit by turning ON the relay. After rectification, the produced DC voltage is used to charge the battery if the SoC of the battery is less than the minimum value. Thereby, under extremely worst conditions (i.e., when both solar PV and AC grid power are not available), the energy stored in the battery can be used to feed the load by providing proper switching signals to switches S_2 and S_3.

MEASURED RESULTS AND VALIDATION

In this section, the performance of the complete proposed novel hybrid dc-dc converter with solar PV, battery, and BLDC motor as a load has been analysed under different dynamic conditions. Using MATLAB-9.0.0 Simulink, different cases have been verified by considering the switching devices and passive components. The measured results are observed under all operating conditions, and corresponding detailed explanations are presented in this section. The performance analysis of the proposed hybrid dc-dc converter has been verified under steady-state and dynamic load/PV power changes.

The solar PV modules with an input voltage of 30 V - 40 V, input current of 24 A, battery with 24 V dc is used as power sources. Here, the reference dc-link voltage across the capacitor C_1 is considered as 48 V dc and the standalone dc load voltage is taken as 240 V dc.

Table 2. Parameters of the solar PV module at a temperature of 25^o c

Parameters	Value
Open-circuit voltage (V_{OC})	30-40 V
Short-circuit current (I_{SC})	7.84 A
Nominal voltage (V_{mpp})	29 V
Nominal current (I_{mpp})	7.35 A
Maximum power (P_{mpp})	213.5 W

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Table 3. Parameters used in simulation

Parameters	Value
Input Voltage (V_{in})	30-40V
Output Voltage (V_o)	240V
Inductors L_1, L_2, L_3	1mH
Capacitors C_1, C_2	440µF
Battery Voltage V_{Bat1}	24V
Switching frequency f_s	20kHZ

Figure 14. Measured results of irradiance, V_{dclink}, PV power during MPPT operation

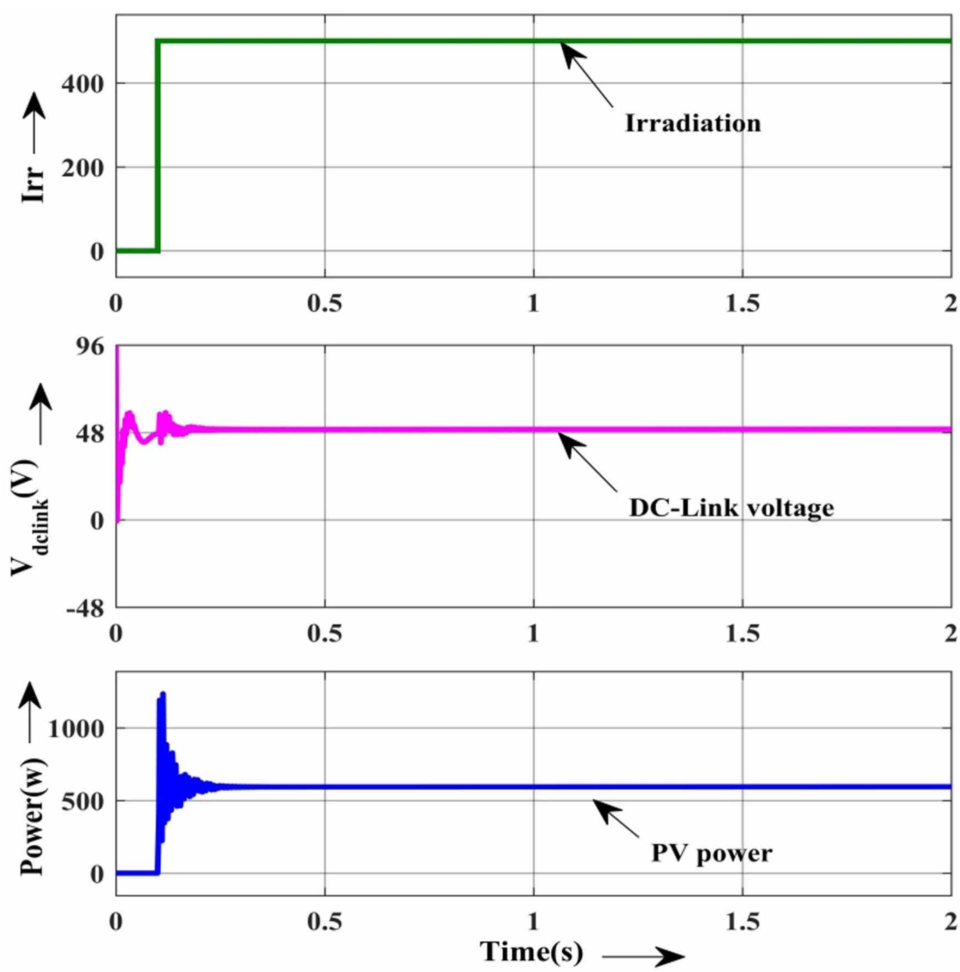

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Figure 14 shows the DC-link voltage across the capacitor C_1 after employing optimal MPPT under the conditions of 500 W/m^2 irradiation level and 25 degree Celsius as panel reference temperature. The DC-link voltage is settling into 48 V, thereby power balance among PV source, battery, and load.

Figure 15 shows simulated waveforms of *I-V* and *P-V* curves for the solar PV array and power tracking in different irradiance. It also shows that the attempts to track the maximum power point (MPP) movement with variations in the operating condition, such as a change in irradiance under 25^{0}C panel temperature. The P&O MPPT algorithm tracks maximum power from the solar PV array under 100w/m^2, 500w/m^{2,} and 1000w/m^2 irradiation level is represented in this figure 7.

Figure 15. Measured results of i-v and p-v characteristics of solar PV

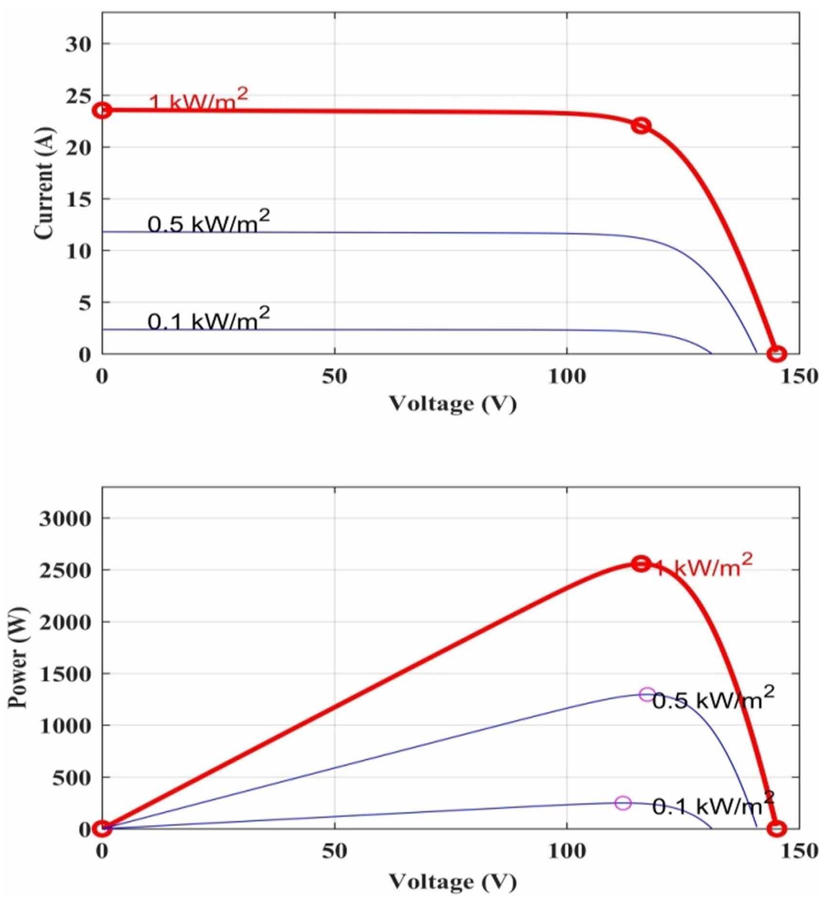

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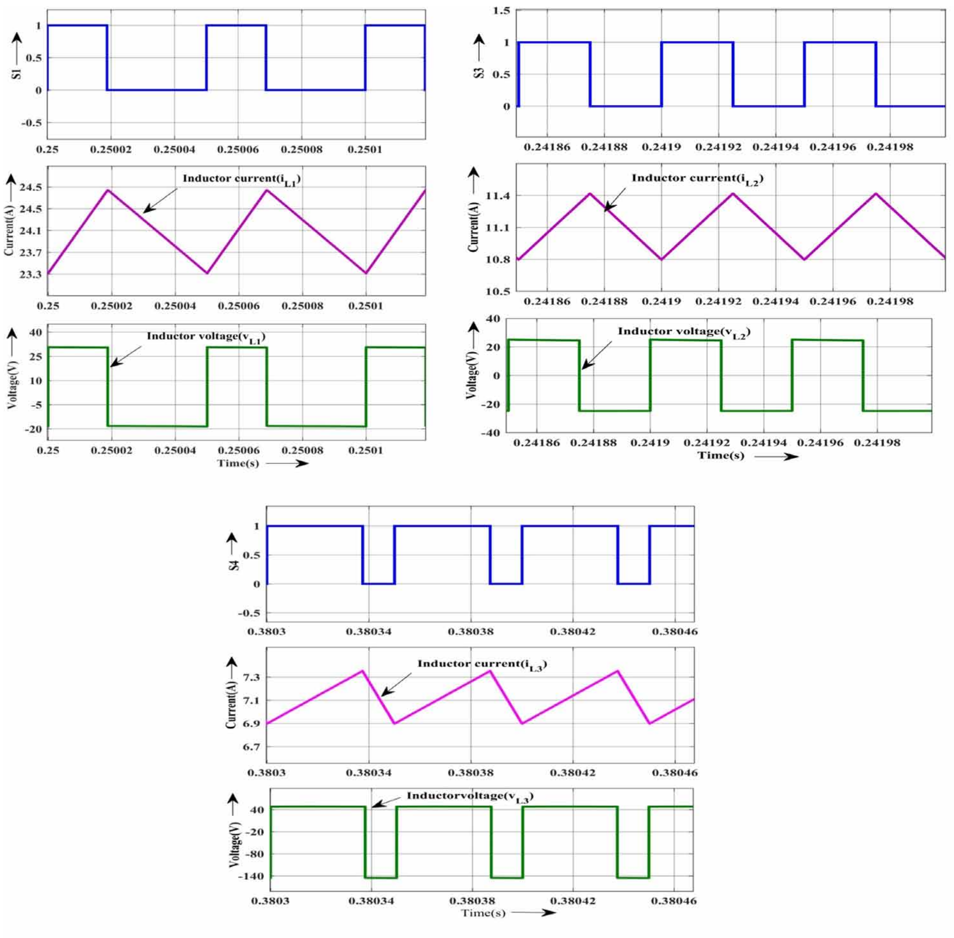
Figure 16. Switching pulse, inductor current ($_{iL)}$, inductor voltage($v_{L)}$ of (a)Inductor 1, (b)Inductor 2, (c)Inductor3



The proposed novel dc-dc converter operates at a fundamental frequency of 20 kHz, and the power transfer is from solar PV to the load. Here in Figure 16 (a), (b), (c) shows the switching pulses, inductor voltages, and inductor current for inductors L_1, $L_{2,}$ and L_3 for the CASE I where there is a surplus of energy and the excess energy stored in the battery.

Measured Results Under Steady-State Conditions

Solar irradiation level is kept at 500w/m^2 at 25^{0}C temperature, and the solar PV array delivers 700 W. Load demand is 420 W, and the excess power is

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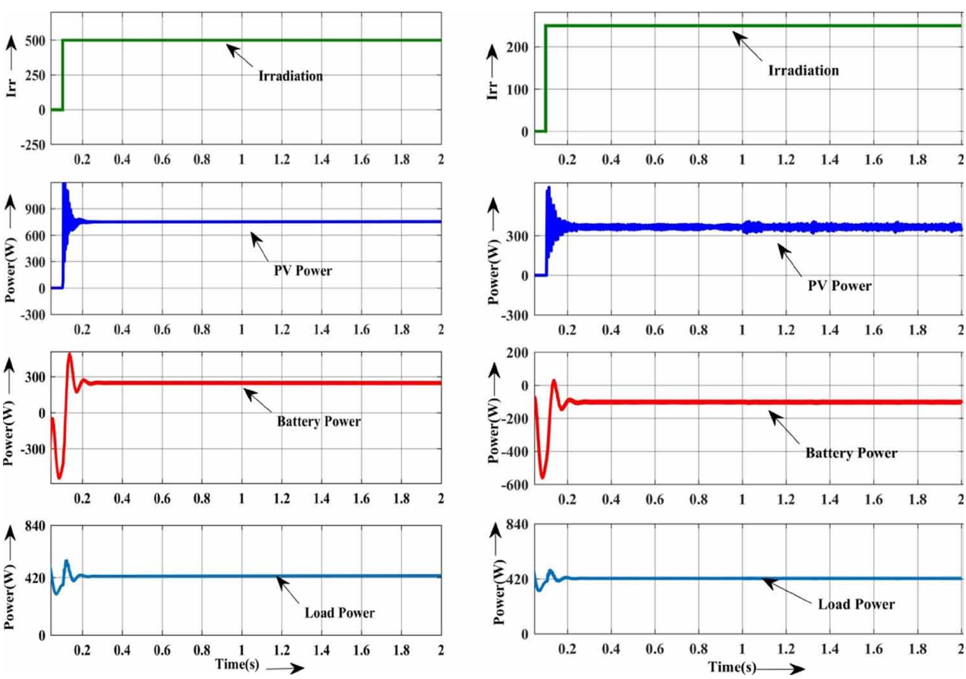
routing to the battery (700 W – 420 W = 280 W) P_{Bat} = 260 W. This case is represented in the below waveform Fig. 17(a). Here the entire available solar PV power is distributed to load and battery storage.

The solar irradiation level is kept at 250 W/m$^{2.}$ The solar PV array can deliver 320 W. When the Load requirement is 420 W. The remaining power is supplied from the battery with a battery power of 120 W. This steady-state result is shown in Fig. 17(b).

Similarly, when there is a shortage in power produced from solar PV at any power range, the remaining load power can be compensated from the battery storage system. With solar irradiation of 300 W/m^2, solar PV array can deliver 440 W. When load power becomes 420 W. Solar power is alone able to supply the power to load. However, the refrigeration effect becomes slower than normal due to a shortage of 20 W of power, in this state, neither battery charges nor discharges. This steady-state result is clearly shown in Fig. 18 (a).

Figure 17. Measured results of steady-state power characteristics during (a) case1-solar PV to battery and load (b) case2-solar PV and battery to load



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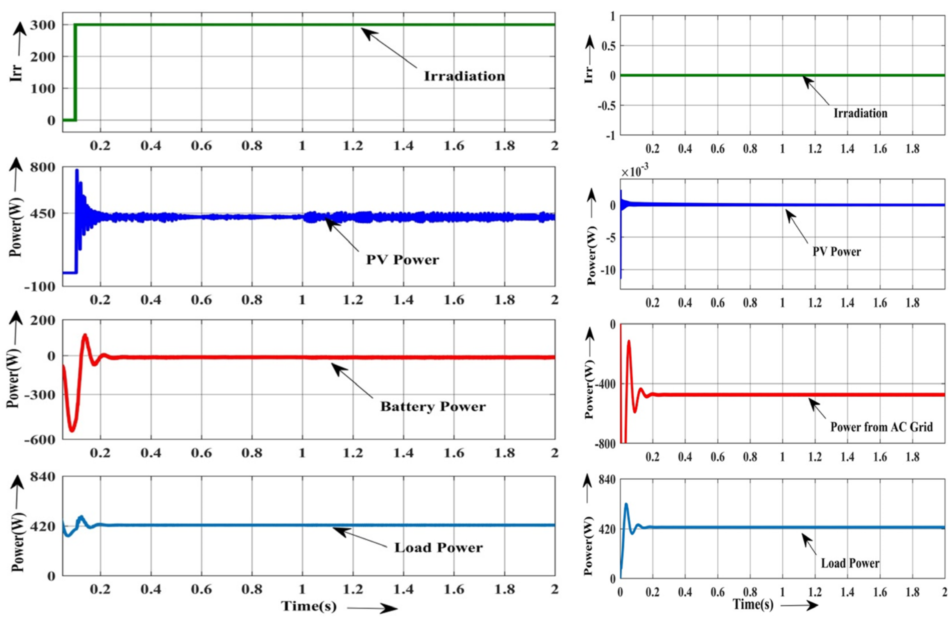
During the absence of solar irradiation, the total load of 420 W can be completely supplied from the AC grid. To validate this, the steady-state result has been obtained and presented in Fig. 9(d). During the night and in rainy seasons the solar isolation is not available. To ensure the continuous operation of the standalone system, the power from the AC grid is supplying to the load after the rectification process. If the SoC level of the battery is less than the maximum value, the power drawn from the AC grid is utilized to charge the battery and satisfies the load. But if the battery SoC level is more than the maximum limit, then the power from AC grid feeds only the load. Here in Figure 18(b) the load power of 420 W is supplying from the AC grid.

Figure 18. Measured results of steady-state power characteristics during (a) case3-solar PV to load (b) case4-Battery to load



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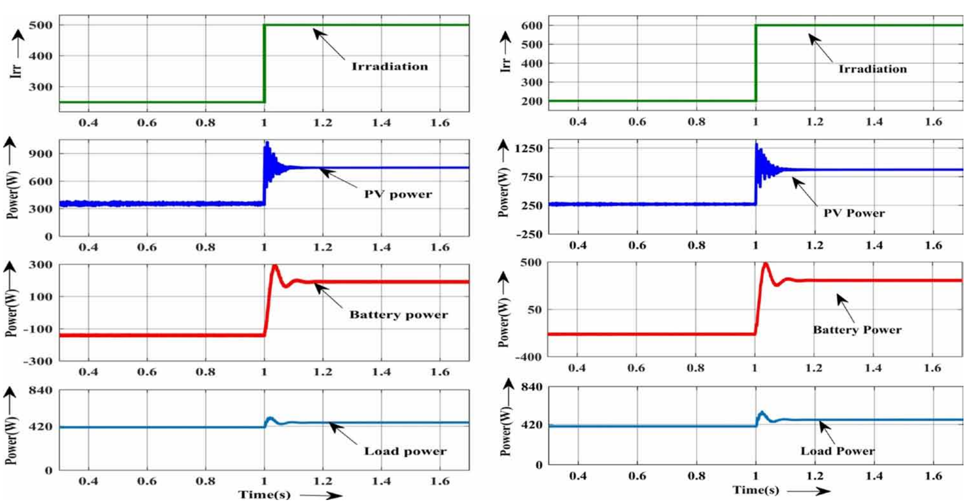
Measured Results Under Dynamic Conditions

Case I: Increase in Solar Irradiation From 250 W/m^2 500 W/m^2

Initially, in Fig. 19(a), solar irradiance is 250 W/m^{2,} and solar PV with MPPT tracking is capable of supplying 320 W. For standalone dc load, the power requirement is 420 W. The MPPT control utilized in this system controls the duty ratio of switch S_1 and tries to extract maximum power from the solar PV. Therefore, the battery makes up for the power deficit of 100 W. In this case, both solar PV and battery together supply the energy to meet the load power. To validate the dynamic conditions, after a second, the solar insolation level is increased to 500 W/m^{2,} and thereby the solar PV module is capable of supplying power of 700 W. In order to extract maximum power from the solar PV, the P&O MPPT algorithm increases the duty ratio of S_1. Here the excess energy is supplied to the battery; hence the constant standalone dc load is maintained. Here, the load power is 420 W, which is well satisfied by the solar PV alone, and the remaining 260 W of solar PV power is charged into the battery.

Figure 19. Measured results of dynamic state power characteristics during (a) Increase in solar irradiation from 250w/m^2 to 500 w/m^2 (b) Increase in solar irradiation from 200w/m^2 to 600 w/m^2



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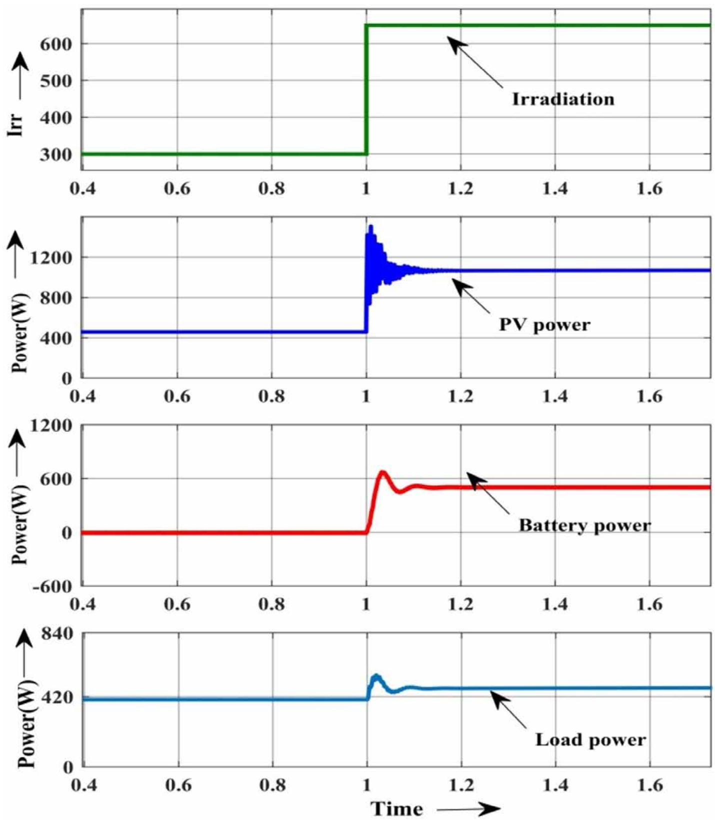
Case II: Increase in Solar Irradiation From 300 W/m² to 650 W/m²

In Fig. 19(b) solar irradiance level is changing from 200 W/m² to 600 W/m². Initially, the solar PV supplies power of 250 W. To meet the load power battery supplies the remaining 80 W of power. When solar irradiance is changed to 600 W/m², the excess energy of 370 W can be supplied to the battery. Thus, the power flow is balanced to operate it as a standalone system.

Figure 20. Measured results of dynamic-state power characteristics during an increase in solar irradiation from 300w/m² to 650 w/m²



In the beginning, the solar irradiation is 300 W/m². Here the solar PV is just sufficient to meet the load power of 420 W. Here, the total PV power generation is directed to load, and the battery should be completely isolated.

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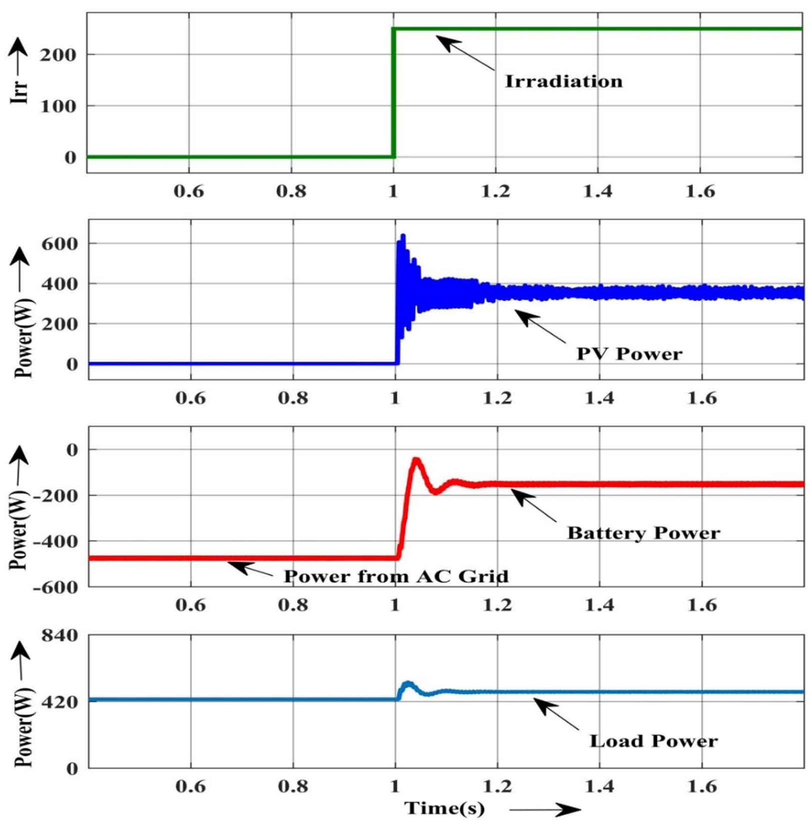
The simulation waveform is given in Fig. 20(a) shows that no energy transfers is made either from or to the battery. After a second, the irradiation becomes 650 W/m^{2,} and the power generation becomes 1000 W. The load power is 420 W, and the remaining 560 W can be stored in the battery.

Case III: Increase in Solar Irradiation From Zero to 250 W/m^2

At first, the system is operating from the power supplied by the AC grid alone. Since solar power is unavailable, the power of 420 W is met by the power drawn from the AC grid through the active rectification process. Let us consider, during this interval. The battery SoC level becomes the maximum value. Therefore, only the load power is met by the power from the AC grid.

Figure 21. Measured results of dynamic-state power characteristics during the increase in solar irradiation from zero to 250 w/m^2



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After 1 second, irradiation increases to 250 W/m2, load power can be met by solar power and battery. The solar power generation is 320 W and the remaining 120 W of power can be supplied from the battery. Under this case, the dynamic condition results are represented in Figure 21.

CONCLUSION

This chapter has proposed a novel hybrid dc-dc converter for a solar-battery-powered standalone system; thereby, a continuous operation of milk vending machine is ensured. The proposed hybrid converter integrates solar PV module, battery storage system, AC power grid, and DC load for efficient power management and can overcome the issues due to shortage of power supply to maintain the quality of milk. The different modes of operation with theoretical waveforms with working details are discussed in detail. The reduced power conversion stage makes the system becomes more compact and achieves higher voltage gain with minimum components count. Many cases have been investigated in detail, such as excess solar PV power generation, a deficit of PV power, and worst-case scenario cases (when both PV power and battery power are not available). And also, to ensure the quality of the milk during continuous rainy conditions or non-sunny hours more than 48 hours, the power automatically consumes from the grid through an active rectification process, which is also validated in this chapter. It validates the MPPT operation, and DC link voltage maintains at a boundary level to balances the power under severe climatic changing conditions. The measured results were obtained and verified under different steady-state and dynamic conditions of the solar PV, and the system achieves power balance under all the cases reported in this chapter. Hence, this proposed idea of work ensures the quality of milk at an optimum level throughout the day under any environmental conditions.

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Chapter 5
Operation of a Hydrogen Storage-Based Smart DC Microgrid

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ABSTRACT

In this chapter, the author presents the operation and power management of the hydrogen storage-based smart DC microgrid (DCMG). In this microgrid, several renewable distributed generations (DGs) such as wind turbine, solar photovoltaic system, solid oxide fuel cell (SOFC), and battery energy storage system are interconnected together and to the various DC and AC loads to form a ring-type low voltage distribution network. An additional storage as Hydrogen storage system has been connected to the dc microgrid for balancing the power at all times in the DCMG, under islanded mode operation, for all practical cases. An architecture of the hydrogen storage-based DC microgrid is suggested mainly for the remote rural area. For the regeneration of the electricity from the stored hydrogen, a SOFC DG system is also used in the proposed DCMG. A control technique is also developed for the operation of the hydrogen storage-based DCMG. The proposed DCMG system provides a reliable and high-quality power supply and will supply the power to all loads (both DC and AC) simultaneously.

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INTRODUCTION

For under-developed and developing countries, the remote rural areas may not have access to the electric power supply from the main grid. The Renewable Energy Sources (RESs), such as Wind Turbine (WT), solar Photovoltaic (PV), and fuel cells Distributed Generations (DGs) are available in the range of 1kW-10MW, which play an important role for the remote rural areas, discussed by Kumars (2014). During the last few years, the RESs are being fast developed, and attracted increased interests of the researchers and utilities due to various environmental, economical, and technical advantages offered by them, presented by Kumars (2015) and Xu (2011). Due to having the intermittent nature of the renewable sources, the direct connection of the renewable sources to the main grid (if it is available in the remote area) would create several problems such as; voltage fluctuations, frequency variation, and protection and stability issues, discussed by Vidal (2013), Wang (2012), Kumars (2015), and Kumar (2020). However, the utility grid may not be available in the remote rural areas. Therefore, the microgrid, which can be AC or DC, provides the facility for the connections of various renewable DGs and Energy Storage Systems (ESSs), discussed by Chen (2012), Aggarwal (2016), and Kumars (2021). The microgrid also provides an opportunity of electrification of remote rural areas, where the grid is not available. The DC Microgrid (DCMG) offers several advantages over ac microgrid as following: better reliability, ease control of each DG by controlling as only DCMG voltage, higher efficiency due to lower losses, no synchronization required for interconnecting many DGs, high power quality, and better controllability due to absence of reactive power, phase and frequency control, discussed by Kumars (2012), Radwan (2012), and Balog (2012).

The work of Kumars (2012) discusses that the Pulse Width Modulation (PWM) based Voltage Source Converters (VSCs) provide several functions as; maintain rated voltage, high quality power conversion, power flow control, fault protection, system balancing, and maximum power point tracking of various DGs. The work of Kumar (2020) discusses that, a control strategy of 3-phase back-to-back PWM VSC is presented for doubly fed induction generator for controlling the power generation in the WT DG. The same control strategy is implemented in the WT DG integrated to the proposed DCMG, in this work.

The demonstrated DCMG consists of various renewable DGs such as Solid Oxide Fuel Cell (SOFC), WT, PV, and ESSs along with the several

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loads. For maintaining the stability of dc microgrid, the power should be balanced at all time in the DCMG. Due to uncertainty and intermittent nature of the renewable sources, the output of the PV and WT DGs are variables. The loads connected are also variable in nature. Thus, in islanded mode, the controllable SOFC DG and ESSs are necessary for balancing the power in the microgrid at all time, which ensures the stability of the DCMG, discussed by Lee (2011). Various ESSs such as battery, supercapacitor, and flywheel are being used. Generally, a Battery Energy Storage System (BESS) is being preferred amongst the several ESSs due to its fast response and long–term output, discussed by Teleke (2009). However, the BESS has limited storage capacity. Beyond the rated capacity of the BESS, under islanded mode, there may be deficit or surplus power in the DCMG, then another energy storage system is required.

To resolve this problem, an additional ESS such as supercapacitors or hydrogen storage can be used along with the BESS in an islanded microgrid. In this work, a Hydrogen Storage System (H_2SS) has been suggested as another ESS for the islanded DCMG along with BESS, which is known as hydrogen storage based DCMG. In this chapter, the control techniques for the operation of hydrogen storage based smart DCMG are also suggested for maintaining the power mismatch at the islanded DCMG under different operating conditions including the fault scenario. The suggested control techniques allow to control the operation of the BESS up to its rated capacity, and thereafter to store the generated surplus power into the H_2SS integrated to the DCMG.

The simulation is carried out to show the robustness and effectiveness of the suggested control techniques for the operation of hydrogen storage based islanded DCMG, for different operating conditions.

ARCHITECTURE OF HYDROGEN STORAGE BASED SMART DC MICROGRID

The proposed architecture of the hydrogen storage based smart dc microgrid along with BESS is shown in Figure 1, which facilitates the connections of various renewable DGs and several loads. The proposed hydrogen storage based DCMG consists of SOFC, WT, and PV DGs, BESS, H_2SS, and various AC and DC loads. The dc cable is needed for integrating various DGs, ESSs, and loads to the DCMG.

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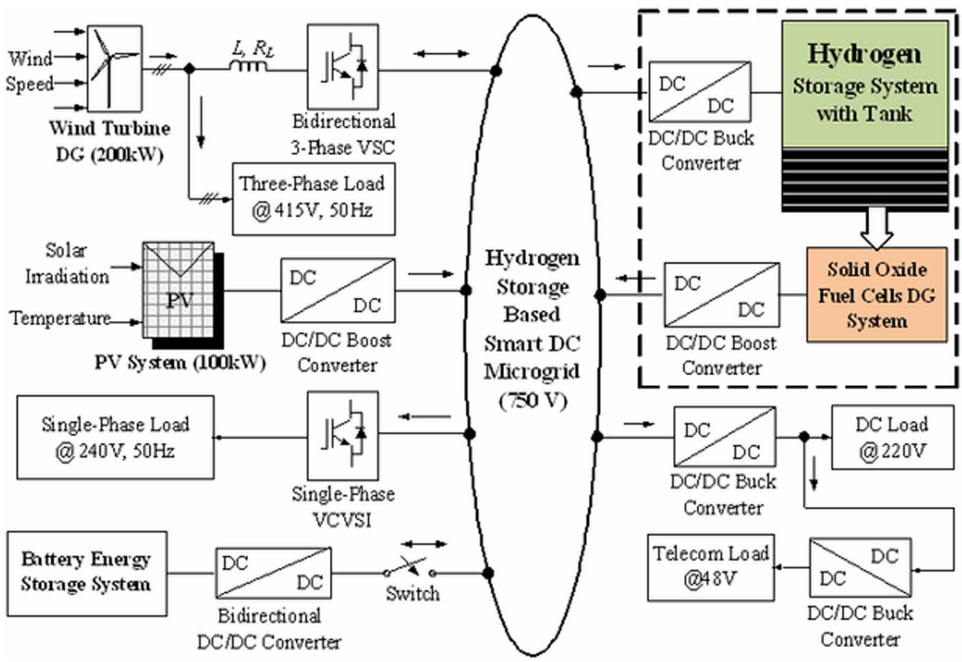
A microgrid can be controlled either by centralized control method or by decentralized control method. In centralized control method, the DG can be controlled through a central controller and the communication link, which causes the degradation of the reliability of the microgrid. While, in decentralized control method, each DG unit is controlled independently by using only dc terminal quantity (i.e. DCMG voltage) without using any communication link between the DGs. The decentralized control maintains the reliability of the microgrid.

Figure 1. Proposed architecture of hydrogen storage based smart dc microgrid



The circulating current between the various DGs is the main issue in the DCMG due to the voltage difference between the DGs. Since, the decentralized control scheme is achieved by using the DCMG voltage as the common reference signals for controlling all DGs, without any communication link. Thus, the decentralized control eliminates the circulating currents among the DGs in the microgrid.

From the study of several literatures, the works of Karlsson (2003), Lin (2005), and Zhang (2009) presents that, a 750V dc voltage of the DCMG

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is considered, in this study, which eliminates the transformer on the load side converters. Since, the standard three-phase line-to-line voltage of the distribution network is 415V (rms). For converting the dc voltage (750V) into three-phase ac voltage (415V, rms), a three-phase Voltage Source Inverter (VSI) is used for connecting three-phase loads and main grid to the DCMG, which operates in the linear as well as under modulation mode with very good modulation index 0.9035. Thus, three-phase VSI maintains rated output ac voltage (415V, line-to-line, rms), directly, without using any transformer.

The WT DG is integrated to the DCMG through the bidirectional three-phase VSC, for managing the bidirectional power flow through it, because a three-phase load is available in the local area of the WT DG. The WT DG consists the doubly fed induction generator. The control scheme of bidirectional three-phase VSC, used for integrating the WT DG to the DCMG, is discussed by Kumar (2012). The same control scheme, as discussed by Kumar (2012), is also used in this work, which is used to maintain almost constant desired rated dc voltage of the microgrid. The PV and SOFC DG systems are integrated to the DCMG through the dc-dc boost converters, for boosting the low generated dc voltage equal to the DCMG voltage. The BESS is connected to the DCMG through the bidirectional dc-dc converter, for controlling the charging and discharging operation of the BESS. The H_2SS is integrated to the DCMG through the dc-dc buck converter. The dc loads operating at dc voltages lower than the DCMG voltage are connected to the DCMG through the dc-dc buck converters. The single-phase ac loads are integrated to the DCMG through the single-phase Voltage Controlled Voltage Source Inverter (VCVSI).

Beyond the charging capacity of the BESS, the continuous generated surplus power is being used to store into H_2SS in the hydrogen form. The electrical energy is converted into hydrogen form by using the electrolysis process through the electrolyzer, discussed by Gyawali (2010) and Mishra (2012). When the WT and PV DGs along with the BESS are unable to fulfill the load demand, then stored hydrogen will be used to regenerate the electricity using the SOFC DG and electrolyzer. The electrochemical reactions in the electrolyzer, using the electricity, are expressed as following, as discussed by Gyawali (2010) and Mishra (2012).

$$\left.\begin{array}{l} Anode:\ 2OH^- \rightarrow \ \frac{1}{2}O_2 \uparrow + H_2O \ + 2e^- \\ Cathode:\ H_2O \ + \ 2e^- \rightarrow \ H_2 \uparrow + 2OH^- \end{array}\right\} \quad (1)$$

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The Valve Regulated Lead Acid (VRLA) battery of 100kW, 375V, 550Ah for 2hrs, is considered for the BESS. Under maximum power generation and minimum load demand case in the DCMG, with considering BESS fully charged, the continuously generated maximum surplus power may be 216kW. Thus, the power rating of the dc-dc buck converter, used for integrating H_2SS including electrolyzer and storage tank to the DCMG, is considered as 270kW. The parameters used for an electrolyzer (40kW rating) of the H_2SS are considered from the work of Gyawali (2010). Thus, for available current rating (735A) of the dc cable, based on maximum current in the DCMG, the parameters of dc cables like as dc resistance (0.047Ω/km) and overall diameter (33.9mm) are considered. The parameters used for the proposed DCMG are given in Appendix. The loads connected to the DCMG are as following: 100kW single-phase ac load, 40kW dc load operating, 10kW telecommunication load, and 50kW three-phase load. Thus, the total rated load is 200 kW.

MODELLING OF HYDROGEN BASED DC MICROGRID

Modelling of the Distributed Generations*:* The dynamic modelling equations for the SOFC, PV, and WT DGs, and various converters are taken, from the works of Gyawali (2010), Kamel (2010), Xia (2013), and Mahmoud (2013). The mechanical power extracted from the available wind is given by (1.1). The power generation by the WT DG as a function of wind speed, is expressed by (1.2).

$$P = \frac{\partial\left(KE_w\right)}{\partial t} C\left(\lambda,\theta\right) = \frac{1}{2} C\left(\lambda,\theta\right)\rho_{air} A_b v_w^3 \tag{1.1}$$

$$\begin{aligned}
&P_{WT} = P_{WT,rated}\left(\frac{v_w^k - v_{w,cut\text{-}in}^k}{v_{w,rated}^k - v_{w,cut\text{-}in}^k}\right); \quad for\ \ v_{w,cut\text{-}in} < v_w < v_{w,rated} \\
&P_{WT} = P_{WT,rated}; \quad for\ \ v_{w,rated} \le v_w \le v_{w,cut\text{-}off} \\
&P_{WT} = 0; \quad for\ \ v_w \le v_{w,cut\text{-}in}\ \ and\ \ v_w > v_{w,cut\text{-}off}
\end{aligned} \tag{1.2}$$

where, P is the mechanical power generated by wind turbine, P_{WT} is the power generation by WT DG, $P_{WT,\mathrm{rated}}$ is the maximum rated power capacity

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of the WT, KE_w is the kinetic energy of wind, v_w is the available wind speed, $v_{\text{w,cut-in}}$ is the cut-in wind speed, $v_{\text{w,cut-off}}$ is the cut-off wind speed ρ_{air} is the air density, A_b is the swept area of the rotor blades, R is the radius of rotor blade, and $C(\lambda,\theta)$ is the power performance coefficient which depends on the blade pitch angle θ and tip-speed ratio λ.

The current-voltage characteristic of the PV array system is expressed by (1.3).

$$I_{PV} = n_p I_{ph} - n_p I_{sat} \left[\exp\left\{ q\left(V_{PV} + I_{PV}\left(n_{se} R_{se} / n_p \right)\right) / n_{se} K T_{cell} A \right\} - 1 \right] - \left\{ \left(n_p V_{PV} / n_{se} \right) + I_{PV} R_{se} \right\} / R_{sh} \quad (1.3)$$

where, I_{PV} is the output current of the PV, I_{ph} is the photo-current, I_{sat} is the diode saturation current, V_{PV} is the output voltage of the PV, q is the charge of electron, K is the Boltzmann constant, T_{cell} is PV operating temperature, A is the diode ideality factor, R_{se} and R_{sh} are the internal series and parallel resistances of the PV, respectively n_{se} is the number of series cells in the PV array system, n_p is the number of PV modules in parallel in the SPV array system.

The SOFC DG output voltage is determined by Nernst's equation, and given by (1.4).

$$V_{FC} = N_{FC}\left[V_{0,FC} + \left(RT/2F \right)\left[\ln\left(p_{H_2} p_{O_2}^{0.5} / p_{H_2O} \right) \right] - R_{FC} I_{FC} \right] \quad (1.4)$$

where, I_{FC} is the rated current of the SOFC DG, N_{FC} is the number of fuel cells connected in series in one stack, V_{FC} is the output voltage of the SOFC DG, $V_{0,FC}$ is ideal standard potential of the SOFC, and R_{FC} is the Ohmic loss of a single SOFC, p_{H_2}, p_{H_2O}, and p_{O_2} are the partial pressures of H_2, H_2O, and O_2 respectively, R is universal gas constant, F is Faraday's constant, T is the operating temperature of the SOFC.

Modelling of Battery Energy Storage System: The dynamic charging and discharging voltage equations of the VRLA battery are expressed by (1.5) and (1.6), from the works of Kumars (2012) and Tremblay (2009).

$$V_{Batt,Ch} = V_{Batt,0} - R_1 i + Exp(t) - \delta \frac{Q_{Batt}}{it - Q_{Batt}/10} \cdot i^* - \delta \frac{Q_{Batt}}{Q_{Batt} - it} \cdot it \quad (1.5)$$

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$$V_{Batt,Dch} = V_{Batt,0} - R_1 i + Exp(t) - \delta \underbrace{\frac{Q_{Batt}}{Q_{Batt} - it} \cdot it}_{\substack{\text{Polarization} \\ \text{Voltage}}} - \delta \underbrace{\frac{Q_{Batt}}{Q_{Batt} - it} \cdot i^*}_{\substack{\text{Polarization} \\ \text{Resistance}}} \quad (1.6)$$

where, $V_{Batt,Dch}$ and $V_{Batt,Ch}$ are discharging and charging voltages of the battery, $V_{Batt,0}$ battery, *Exp(t)* is voltage of the exponential zone, *it* ($=\int idt$) is actual charge of the is constant voltage of the battery, δ is the polarization constant, *Q* is capacity of the battery, *i* is current in the battery, *i** is filtered current, and R_1 is resistance of the battery.

Modelling of Hydrogen Storage System: The modeling of an alkaline type electrolyzer have been described by (1.7)-(1.11), from the works of as discussed by Gyawali (2010), Mishra (2012), and Karim (2010). The reversible voltage (V_{rev}) or thermodynamic cell voltage (V_0) solely depends on Gibb's energy (ΔG), is expressed by (1.7).

$$\left. V_{rev} = \frac{\Delta G}{FN_e} = V_0, \quad and \quad V_{Elz,0} = V_0 \times N_{cell,Elz} \right\} \quad (1.7)$$

where, $V_{Elz,0}$ is no load voltage of electrolyzer, N_e is number of electrons in one reaction, and $N_{cell,Elz}$ is number of cells connected in series in one stack.

The Faraday efficiency (η_I) or current efficiency of the electrolyzer is expressed by (1.8). The volumetric flow rate of hydrogen ($\mathring{U}_H$), hydrogen molar production rate ($M_{H,Prod}$) as a function of current, and *V-I* relationship of electrolyzer, are expressed by (1.9), (1.10), and (1.11), respectively.

$$\left. \begin{array}{l} \eta_I = \dfrac{J_{Elz}^2}{K_1 + J_{Elz}^2} K_2; \quad where, \; J_{Elz} = \dfrac{I_{Elz}}{A_{Elz}}, \; I_{Elz} = \dfrac{P_{Elz}}{V_{Elz,0}} \\ \quad and \; K_1 = 50 + 2.5T_{Elz}, \; K_2 = 1 - 0.00075T_{Elz} \end{array} \right\} \quad (1.8)$$

$$\dot{U}_H = M_{H,prod} \times v_t \times 3600(Ltr / hr) \quad (1.9)$$

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$$\left. M_{H,prod} = \eta_I I_{Elz} \frac{N_{Elz}}{FN_e} \quad and \quad I_{Elz} = N_{Stack,Elz} * I_{Elz,Stack} \right\} \tag{1.10}$$

$$\left. \begin{array}{l} V_{cell,Elz} = V_0 + I_{Elz,stack}\left(\frac{r_1 + r_2 T_{Elz}}{A_{Elz}}\right) + V_1 \log\left(\frac{m_1 + (m_2 / T_{Elz}) + (m_3 / T_{Elz}^2)}{A_{Elz}} I_{Elz,stack} + 1\right) \\ and \;\; V_{Elz} = V_{cell,Elz} * N_{cell,Elz,stack} \end{array} \right\} \tag{1.11}$$

where, J_{Elz} is current density of electrolyzer, I_{Elz} is total rated current of electrolyzer, A_{Elz} is area of a stack of electrolyzer, P_{Elz} is rated power of electrolyzer, K_1 and K_2 are the parameters related to Faraday efficiency, v_t is molar volume of ideal gas, $V_{cell,Elz}$ is voltage across one cell of electrolyzer, $I_{Elz,,stack,}$ is current in one stack of electrolyzer, $N_{stack,Elz,}$ is number of parallel stacks of electrolyzer, T_{Elz} is electrolyzer temperature, V_{Elz} is rated load voltage of electrolyzer, r_1 and r_2 are the parameters of Ohmic resistances, V_1 is over voltage of electrolyzer, and m_1, m_2, m_3, are over voltage coefficients of electrolyzer.

Modelling of DC-DC Converters: The bidirectional dc-dc converter and dc-dc buck converter are presented in Figures 2 (a) and (b), respectively, and considered from the work of Kumars (2012). The average voltage of inductor and average capacitor current equations of dc-dc buck converter, as shown in Fig. 1.2(b), are expressed by (1.12) and (1.13) as following.

$$\left. \frac{d}{dt}\langle i_L \rangle = \frac{\langle v_{in} d \rangle}{L_{buck}} - \frac{\langle v_{o\_buck} \rangle}{L_{buck}} \quad and \quad \frac{d}{dt}\langle v_{o\_buck} \rangle = \frac{\langle i_L \rangle}{C_{o\_buck}} - \frac{\langle v_{o\_buck} \rangle}{R_{L,dc} C_{o\_buck}} \right\} \tag{1.12}$$

$$\left. \frac{d}{dt} I_L = \frac{D V_{in}}{L_{buck}} - \frac{V_{o\_buck}}{L_{buck}} \quad and \quad \frac{d}{dt} V_{o\_buck} = \frac{I_L}{C_{o\_buck}} - \frac{V_{o\_buck}}{R_{L,dc} C_{o\_buck}} \right\} \tag{1.13}$$

where, V_{o_buck} and V_{dc} are output and input dc voltage, respectively, D is average value of duty cycle, C_{o_buck} and L_{buck} is output capacitor and inductor of buck converter, respectively, I_o is average value of output current, I_L is current through the inductor, and $R_{L,dc}$ is the resistive dc load across the output terminals.

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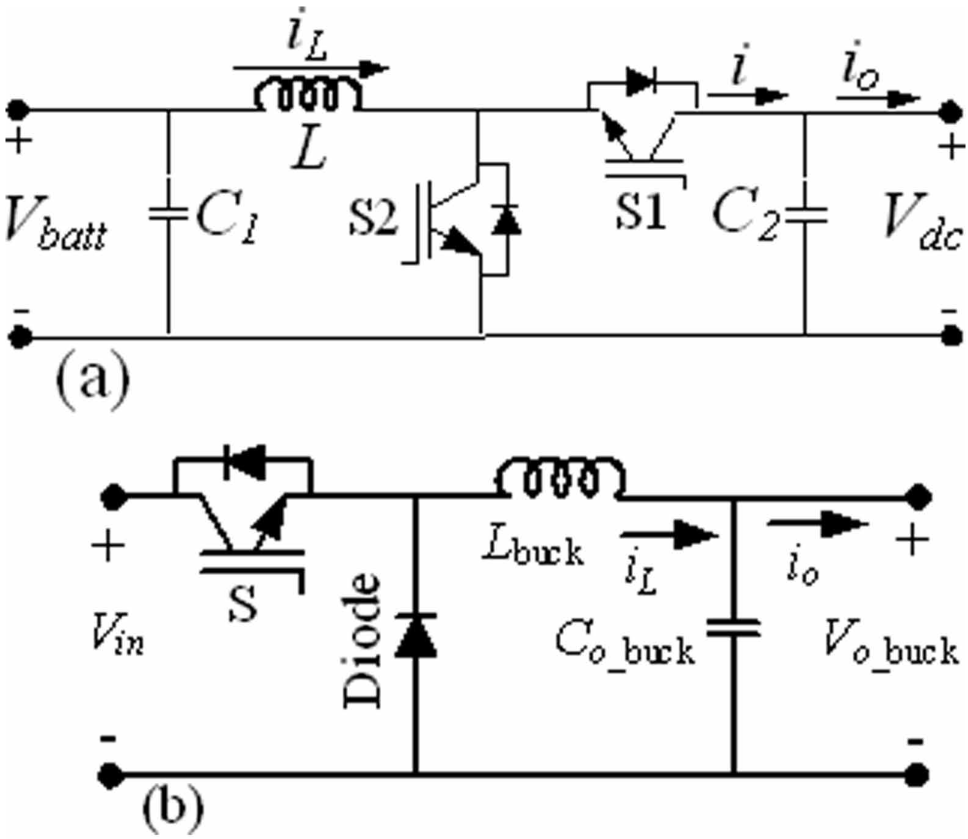
Figure 2. (a) DC-DC bidirectional converter and (b) DC-DC buck converter



With considering small perturbations for all quantities as,

$$v_{in} = V_{in} + \tilde{v}_{in},\ v_{o\_buck} = V_{o\_buck} + \tilde{v}_{o\_buck},\ d = D + \tilde{d},\ i_L = I_L + \tilde{i}_L,\ and\ i_o = I_o + \tilde{i}_o,$$

and by solving the equations (1.12) and (1.13), the small signal state space model of dc-dc converter in buck mode is represented by equation (1.14).

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$$\left.\begin{aligned}&\frac{d}{dt}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{o\_buck}\end{bmatrix}=\begin{bmatrix}0 & -1/L_{buck}\\ \dfrac{1}{C_{o\_buck}} & \dfrac{-1}{R_{L,dc}C_{o\_buck}}\end{bmatrix}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{o\_buck}\end{bmatrix}+\begin{bmatrix}\dfrac{D}{L_{buck}}\\ 0\end{bmatrix}\tilde{v}_{in}+\begin{bmatrix}\dfrac{V_{in}}{L_{buck}}\\ 0\end{bmatrix}\tilde{d}\\ &output\ (Y_{buck})=\begin{bmatrix}\tilde{v}_{o\_buck}\end{bmatrix}=\begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{o\_buck}\end{bmatrix},\ where,\ V_{o\_buck}=V_{Elz}\ and\ V_{in}=V_{dc}\end{aligned}\right\} \tag{1.14}$$

The quantities represented as v_{in}, v_{o_buck}, i_L, i_o, and d, are instantaneous values. The quantities represented as V_{in}, V_{o_buck}, I_L, I_o, and D, are average values. The quantities represented with tilde,

$$\tilde{v}_{in},\ v_{o\_buck},\ \tilde{v}_{dc},\ \tilde{v}_{Elz},\ \tilde{i}_L,\ \tilde{i}_o,\ and\ \tilde{d},$$

are perturbations in the various quantities. The controlled transfer function, $G_{C\_buck(s)}$ of dc-dc buck converter are expressed by using (1.14), and is given by (1.15).

$$G_{C\_buck}(s)=\left.\frac{\tilde{v}_{Elz}(s)}{\tilde{d}(s)}\right|_{\tilde{v}_{dc}=0}=\frac{V_{dc}}{L_{buck}C_{o\_buck}s^2+\left(L_{buck}/R_{L,dc}\right)s+1} \tag{1.15}$$

The equations (1.16) and (1.17) represent the small signal state space model of the BDC, as shown in Fig. 1.2(a), for the buck as well as the boost mode, respectively.

$$\left.\begin{aligned}&\frac{d}{dt}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{Batt}\end{bmatrix}=\begin{bmatrix}-R_1/L & -1/L\\ 1/C_1 & 0\end{bmatrix}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{Batt}\end{bmatrix}+\begin{bmatrix}V_{dc}/L\\ 0\end{bmatrix}\tilde{d}+\begin{bmatrix}D/L\\ 0\end{bmatrix}\tilde{v}_{dc}+\begin{bmatrix}0\\ -1/C_1\end{bmatrix}\tilde{i}_o\\ &output\ (Y_{BDC\_buck})=\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{Batt}\\ \tilde{i}_o\end{bmatrix}=\begin{bmatrix}1 & 0\\ 0 & 1\\ 1 & 0\end{bmatrix}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{Batt}\end{bmatrix},\ where,\ V_o=V_{Batt}\ and\ V_{in}=V_{dc}\end{aligned}\right\} \tag{1.16}$$

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$$\left.\begin{aligned} &\frac{d}{dt}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{dc}\end{bmatrix}=\begin{bmatrix}-R_1/L & -(1-D)/L\\ (1-D)/C_2 & 0\end{bmatrix}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{dc}\end{bmatrix}+\begin{bmatrix}-V_{dc}/L\\ -I_L/C_2\end{bmatrix}\tilde{d}+\begin{bmatrix}1/L\\ 0\end{bmatrix}\tilde{v}_{Batt}+\begin{bmatrix}0\\ -1/C_2\end{bmatrix}\tilde{i}_o\\ &output\ (Y_{BDC\_boost})=\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{dc}\\ \tilde{i}_o\end{bmatrix}=\begin{bmatrix}1 & 0\\ 0 & 1\\ (1-D) & 0\end{bmatrix}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_{dc}\end{bmatrix}+\begin{bmatrix}0\\ 0\\ -I_L\end{bmatrix}\tilde{d},\ where,\ V_{in}=V_{Batt}\ and\ V_o=V_{dc}\end{aligned}\right\} \tag{1.17}$$

The controllable transfer functions of the BDC in buck mode have been expressed using (1.16), and are given by (1.18). The controllable transfer functions of the BDC in boost mode have been derived from (1.17), and expressed by (1.19).

$$\left.\begin{aligned} &G_{C,1\_buck}(s)=\left.\frac{\tilde{i}_L(s)}{\tilde{d}(s)}\right|_{\tilde{v}_{dc}=\tilde{i}_o=0}=\frac{V_{dc}C_1 s}{LC_1 s^2+R_1C_1 s+1}=\left.\frac{\tilde{i}_o(s)}{\tilde{d}(s)}\right|_{\tilde{v}_{dc}=\tilde{i}_o=0}=G_{C,3\_buck}(s)\\ &G_{C,2\_buck}(s)=\left.\frac{\tilde{v}_{Batt}(s)}{\tilde{d}(s)}\right|_{\tilde{v}_{dc}=\tilde{i}_o=0}=\frac{V_{dc}}{LC_1 s^2+R_1C_1 s+1}\end{aligned}\right\} \tag{1.18}$$

$$\left.\begin{aligned} &G_{C,1\_boost}(s)=\left.\frac{\tilde{i}_L(s)}{\tilde{d}(s)}\right|_{\tilde{v}_{Batt}=\tilde{i}_o=0}=\frac{V_{dc}C_2 s+(1-D)I_L}{LC_2 s^2+R_1C_2 s+(1-D)^2}\\ &G_{C,2\_boost}(s)=\left.\frac{\tilde{v}_{dc}(s)}{\tilde{d}(s)}\right|_{\tilde{v}_{Batt}=\tilde{i}_o=0}=\frac{(1-D)V_{dc}-I_L(Ls+R_1)}{LC_2 s^2+R_1C_2 s+(1-D)^2}\\ &G_{C,3\_boost}(s)=\left.\frac{\tilde{i}_o(s)}{\tilde{d}(s)}\right|_{\tilde{v}_{Batt}=\tilde{i}_o=0}=\frac{(1-D)V_{dc}C_2 s+(1-D)^2 I_L}{LC_2 s^2+R_1C_2 s+(1-D)^2}-I_L\end{aligned}\right\} \tag{1.19}$$

where, V_o and V_{in} are the output and input average voltage of the BDC, respectively; L is the inductor of the BDC; C_1 and C_2 are the capacitors of the BDC; V_{Batt} is the battery voltage; R_1 is the internal resistance of the battery. The quantities with tilde, $\tilde{v}_{dc},\ \tilde{v}_{Batt},\ \tilde{i}_L,\ \tilde{i}_o,\ and\ \tilde{d}$ represent the perturbations in various quantities.

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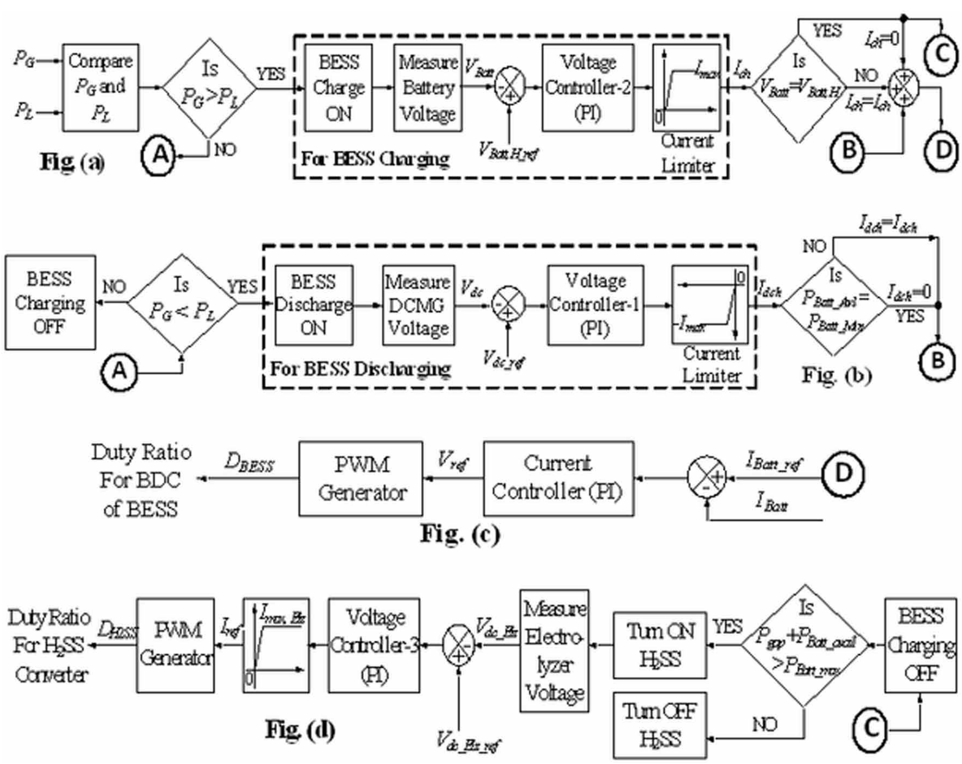
DEVELOPED CONTROL TECHNIQUES AND FLOW CHART FOR POWER MANAGEMENT

The control techniques for the operation of the hydrogen storage based DCMG along with BESS are suggested, as shown in Figures 3 (a) – (d), under islanded mode, for all cases. In the suggested control techniques, the power generations by both WT and PV DGs (P_{G1}) are continuously compared with the total load demand (P_L) in the DCMG, as shown in Figure 3(a). When the generated power (P_{G1}) is less than the load demand, this power mismatch is initially fulfilled by the controllable SOFC DG and then by discharging the BESS. During the surplus power generation case, the suggested control techniques allow initially to charge the BESS up to its full charging capacity first and then store the continuously generated surplus power into the hydrogen storage system in the hydrogen form, for all different operating conditions.

Figure 3. Developed control techniques for operation of hydrogen storage based DCMG



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In the suggested control techniques, two PI voltage controllers and one PI current controller are used for controlling of operation of the BDC for the BESS. In case of deficit power, the deficit power is initially fulfilled by the SOFC DG and then by discharging of the BESS. During the BESS discharging, as shown in Figure 3(b), the measured DCMG voltage (V_{dc}) is compared with its reference voltage (V_{dc_ref}), and this error is sent to PI controller-1, which generates a reference current signal (I_{dch}) for current controller. This reference signal will be high (I_{dch}) or zero depending on the power available status of the BESS (P_{Batt_avail}).

In case of surplus power generation, the measured battery voltage (V_{Batt}) is compared with its high voltage reference value ($V_{Batt\_H\_ref}$), as shown in Figure 3(a), and this voltage error is sent to the PI voltage controller-2 for controlling the charging of the BESS, which provides another reference current signal (I_{ch}) for current controller. This signal will be high (I_{ch}) or zero depending on the charging status of the BESS (V_{Batt_max}).

The combination of these two reference current signals (I_{dch} and I_{ch}) provides a new reference current signal (I_{Batt_ref}) for the current controller, as shown in Figures 3(a) and (c), and is compared with the measured current of the BESS (I_{Batt}), as shown in Figure 3(c). This current difference is sent to the PI current controller, which generates a controlled reference voltage signal. This controlled signal is sent to the PWM generator for providing the controlled duty ratio (D_{BESS}) for the BDC of the BESS, under various operating scenarios.

When the battery is fully charged, and still the DGs are generating the surplus power, continuously, then the hydrogen storage system is turned on to store the surplus power. As shown in Figure 3(d), the measured electrolyzer voltage (V_{dc_Elz}) is compared with its reference voltage ($V_{dc\_Elz\_ref}$), and this error of voltage is sent to the PI voltage controller-3 of the hydrogen storage system. The output of this PI controller generates a reference signal, which is given to the PWM generator to generate the controlled duty ratio (D_{H2SS}) for the dc-dc buck converter of the hydrogen storage system.

A flow chart for the power management in the hydrogen storage based smart DCMG has also been presented in Figure 4 In this, measure and observe the power generations by both WT and PV DGs (P_{G1}), total load demand (P_L), and BESS output power continuously, and then check the generation is surplus or deficit power. If generation is surplus and BESS is not fully charged, then start the charging BESS up to its rated capacity. After fully charging the BESS, if still there is surplus power then store this surplus power into the H_2SS. If the generation meet the load demand exactly, then there is no role

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of BESS and H_2SS. If the generation (P_{G1}) is less than the total load demand (P_L), then SOFC DG is turned on to generate the power, using the stored hydrogen, for meeting the load demand of the DCMG. Beyond the generating capacity of SOFC DG, if still load demand is not fully meet, then BESS will be discharged to meet the load demand. If still load demand is not fulfilled, then reduce the loads for balancing the power in the DCMG. After this, the generations and/or loads are continuously observed to take next decision. If the generations and/or loads are changed then repeat the whole process.

DETERMINATION OF PARAMETERS FOR DC-DC CONVERTERS

The dc-dc buck converter is widely used to obtain the step-down dc voltage. The topology of the dc-dc buck converter is shown in Fig. 2 (b). In the Continuous Conduction Mode (CCM), the relation between the peak-to-peak ripple inductor current and the inductor of the dc-dc buck converter can be derived from the work of Mohan (2001), and is expressed by (1.20), and the critical inductance ($L_{\text{buck,criti}}$) is expressed by (1.21).

$$\left.\begin{aligned} &\Delta I_L = \frac{\left(V_{in} - V_{o\_buck}\right)D}{F_{sw}L_{buck}} = \frac{V_{in}D\left(1-D\right)}{F_{sw}L_{buck}}; \quad where\ \Delta I_L \le 0.1 I_L \\ &L_{buck} \ge \frac{10V_{in}D\left(1-D\right)}{F_{sw}I_L}\ \ or\ L_{buck} \ge \frac{10\left(1-D\right)V_{o\_buck}}{F_{sw}I_o} \\ &V_{o\_buck} = V_{in}D,\ and\ \ \frac{V_{o\_buck}}{I_o} = R_{L,dc} \end{aligned}\right\} \tag{1.20}$$

$$\left.\begin{aligned} &\left(1-D\right) \le \frac{2L_{buck}}{R_{L,dc}}F_{sw} or L_{buck} \ge \frac{\left(1-D\right)V_{o\_buck}}{2F_{sw}I_o} \\ &L_{buck,criti} = \frac{D\left(1-D\right)V_{in}}{2F_{sw}I_{L,\max}}; \quad where,\ I_{L,\max} = I_{o,\max}\ \ and\ \ L_{buck} < L_{buck,crit} \end{aligned}\right\} \tag{1.21}$$

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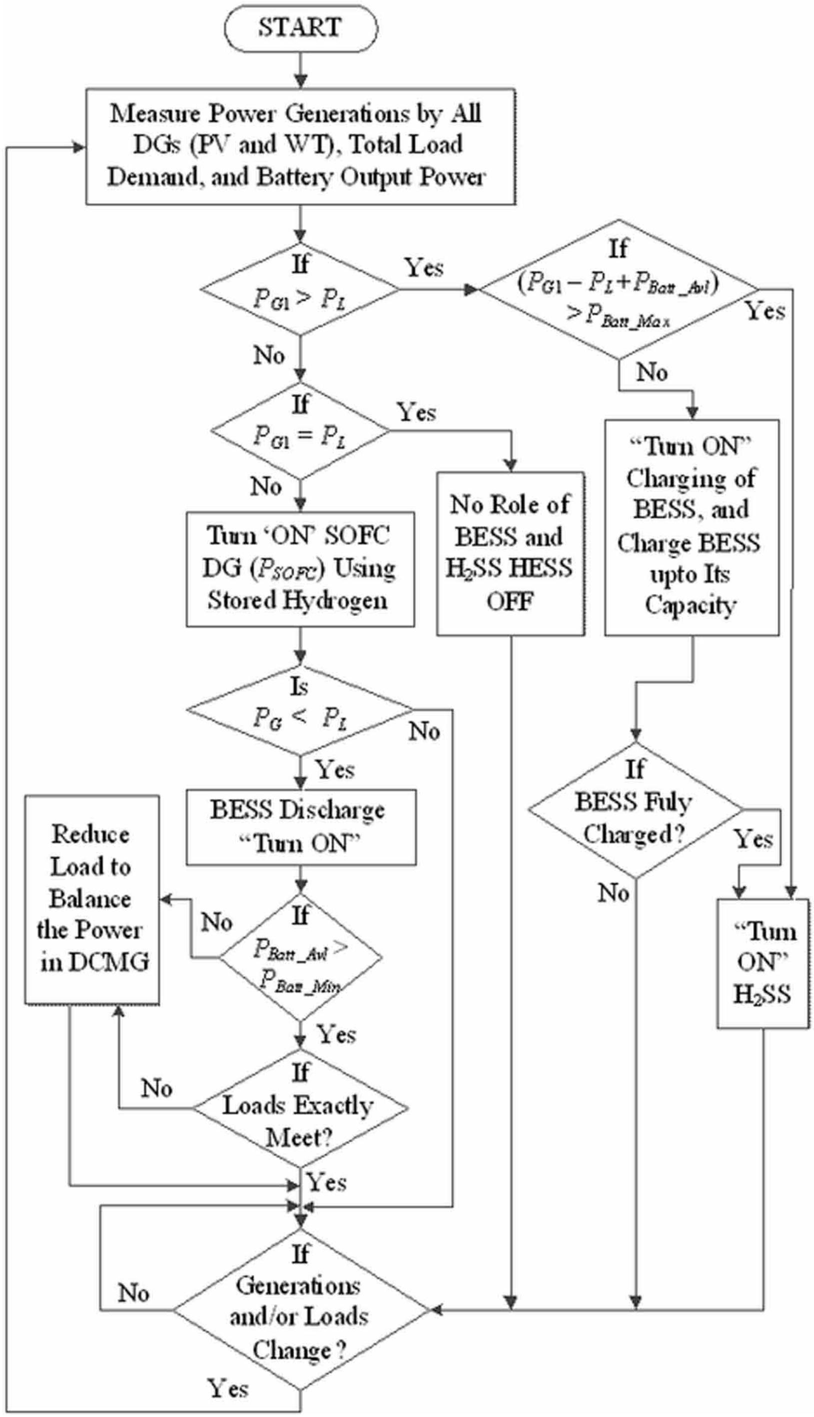
Figure 4. Flow chart for power management in the hydrogen storage based DCMG



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The expression for output capacitor and input capacitor of the dc-dc buck converter can be derived as following by (1.22).

$$\left.\begin{aligned}
&C_{o_buck} = \frac{DV_{o_buck}}{\Delta V_{o_buck} F_{sw} R_{L,dc}} \\
&Where,\ \ \frac{\Delta V_{o_buck}}{V_{o_buck}} \le 1\%\ \ and\ \ \frac{\Delta V_{in}}{V_{in}} \le 1\% \\
&Then,\ \ C_{o_buck} \ge \frac{100D}{F_{sw} R_{L,dc}}\ \ and\ \ C_{in_buck} \ge \frac{1}{8}\left(\frac{\Delta I_L}{\Delta V_{in} F_{sw}}\right)
\end{aligned}\right\} \tag{1.22}$$

where, V_{in} and V_{o_buck} are the input dc voltage and average output dc voltage of the dc-dc buck converter, respectively, D is the average duty cycle, F_{sw} is the switching frequency of the converter, L_{buck} and C_{o_buck} is the inductor and output capacitor of the dc-dc buck converter, respectively, C_{in_buck} is the input capacitor of the dc-dc buck converter, I_o is the average output current, I_L is the current through the inductor, and $R_{L,dc}$ is the dc load connected across the output terminals of the dc-dc converter.

The dc-dc boost converter is widely used to obtain the step-up dc voltage. The topology of a dc-dc boost converter is shown in Fig. 1.2 (a). In the continuous conduction mode, the relation between the peak-to-peak ripple inductor current and the inductor of the dc-dc boost converter can be derived from the works of Mohan (2001) and Hasaneen (2008), and is given by (1.23), and the critical inductance ($L_{\text{boost,criti}}$) is expressed by (1.24).

$$\left.\begin{aligned}
&\Delta I_L = \frac{DV_{in}}{F_{sw} L_{boost}} = \frac{D(1-D)^2 I_L V_{o_boost}}{F_{sw} L_{boost} I_o},\ \ where\ \Delta I_L \le 0.1 I_L \\
&Therefore,\ \ L_{boost} \ge \frac{10D(1-D)^2 V_{o_boost}}{F_{sw} I_o}\ \ and\ \ \frac{V_{o_boost}}{I_o} = R_{L,dc}
\end{aligned}\right\} \tag{1.23}$$

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$$For \quad CCM: (1-D) \le \sqrt{\frac{2L_{boost}F_{sw}}{DR_{L,dc}}} \;\; or \;\; L_{boost\_criti} \ge \frac{D(1-D)^2 V_{o\_buck}}{2F_{sw}I_o} \Bigg\} \tag{1.24}$$

The expressions for the output capacitor and input capacitor of the dc-dc boost converter are given by (1.25).

$$\left.\begin{aligned} & C_{o\_boost} = \frac{DI_o}{\Delta V_{o\_boost}F_{sw}} = \frac{DV_{o\_boost}}{\Delta V_{o\_boost}F_{sw}R_{L,dc}} \\ & For \quad \frac{\Delta V_{o\_buck}}{V_{o\_buck}} \le 1\%, \;\; C_{o\_boost} \ge \frac{100D}{F_{sw}R_{L,dc}} \\ & C_{in\_boost} \ge \frac{1}{8}\left(\frac{\Delta I_L}{\Delta V_{in}F_{sw}}\right), \;\; For \quad \frac{\Delta V_{in}}{V_{in}} \le 1\% \end{aligned}\right\} \tag{1.25}$$

where, V_{in} and V_{o_boost} are the input dc voltage and average output dc voltage of the dc-dc boost converter, respectively, D is the average duty cycle, F_{sw} is the switching frequency of the converter, L_{boost} and C_{o_boost} is the inductor and output capacitor of the dc-dc boost converter, respectively, C_{in_boost} is the input capacitor of the dc-dc boost converter, I_o is the average output current, I_L is the current through the inductor, and $R_{L,dc}$ is the dc load connected across the output terminals of the dc-dc converter.

The PI controllers' parameters of both dc-dc converters, using the various controllable transfer functions as given in (1.15), (1.18), and (1.19), are determined by using Bode-Plot based technique as given in Table 1.

Table 1. Parameters of PI controllers of both dc-dc converters (BDC and Buck)

PI Controllers	Proportional Gain (K_P)	Integral Gain (K_I)
Voltage Controllers for BDC	$K_{P\_V} = 246.2\times10^{-6}$	$K_{I\_V} = 9.848\times10^{-3}$ s^{-1}
Current Controllers for BDC	$K_{P_c} = 353\times10^{-6}$	$K_{I_c} = 89.72\times10^{-3}$ s^{-1}
Voltage Controllers for Buck Converter	$K_{P\_V} = 2.5427\times10^{-3}$	$K_{I\_V} = 40.68\times10^{-3}$ s^{-1}

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OPERATIONAL ANALYSIS WITH SIMULATION RESULTS

To show the effectiveness and robustness of the proposed hydrogen storage based smart DCMG along with the suggested control techniques, the performance analysis of the suggested control techniques for the operation of the hydrogen storage based DCMG, is carried out for various operating scenarios under islanded mode, in the MATLAB/Simulink environment. Here, the simulation results are considered for the fault scenario.

Performance Analysis under Fault Condition

The performance analysis of the suggested control techniques for the operation of the hydrogen storage based smart DCMG, with a dc fault on the DCMG, is carried out under islanded mode. In this mode, the power generations by the WT DG (200kW at rated wind speed 11.3 m/s) and by the PV system (100kW at standard test condition i.e. 25^0C and 1000W/m^2) are constant, and SOFC DG is turned off during the whole operation for this case because there is no need of the SOFC DG in case of the surplus power generation, continuously, as shown in Figure 5(a). The power consumed by the single-phase AC load, telecommunication load, and DC load remains the same as during the fault and the post-fault (as in the pre-fault condition), while three-phase load in the local area of the WT DG experiences slight variation due to transients under the faulty operation, as shown in Figure 5(b), during the fault, pre-fault, and post-fault periods.

At t=1.2s, a dc fault with fault resistance (R_f =100 mΩ) is occurred on the DCMG system, which causes to decrease the DCMG voltage from 750V to 580V, as shown in Figure 6. The power consumed by the total load has also slight variations during the fault, as shown in Figure 7. The total power generation (surplus power generation case during the whole operation), total load demand, and the power mismatch are shown in Figure 7.

During t=0 to t=1s, initially, the BESS is charged by the part of generated surplus power, and as BESS gets fully charged (as shown in Figure 8), then the remaining generated power is stored in the hydrogen storage system, as shown in Figure 9. During t=1s to t=3s, the generated surplus power has been continuously stored into the hydrogen storage system, even during the fault (as shown in Figure 9), because the BESS has already been fully charged. The current and voltage of the electrolyzer of the hydrogen storage system,

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and stored hydrogen amount, are also shown in Figure 9. A few part of the surplus power is also dissipated in the fault resistance during the fault, as shown in Figure 6. When the fault has been finished at *t*=1.4s, the DCMG system will operate in the normal mode, as shown in Figures 5 – 9.

Figure 5. (a) Power generations by WT, PV and SOFC DGs, and (b) Various loads connected to the DCMG during fault, pre-fault, and post-fault

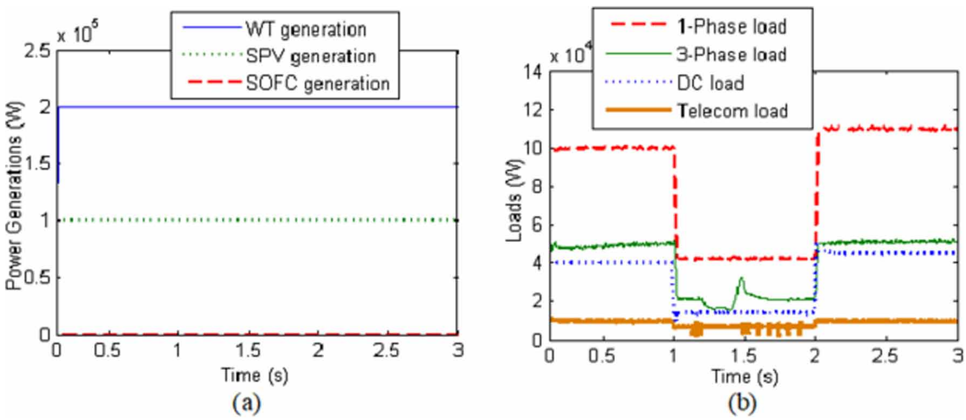

Figure 6. Fault power, fault current, and DCMG voltage during fault, pre-fault, and post-fault

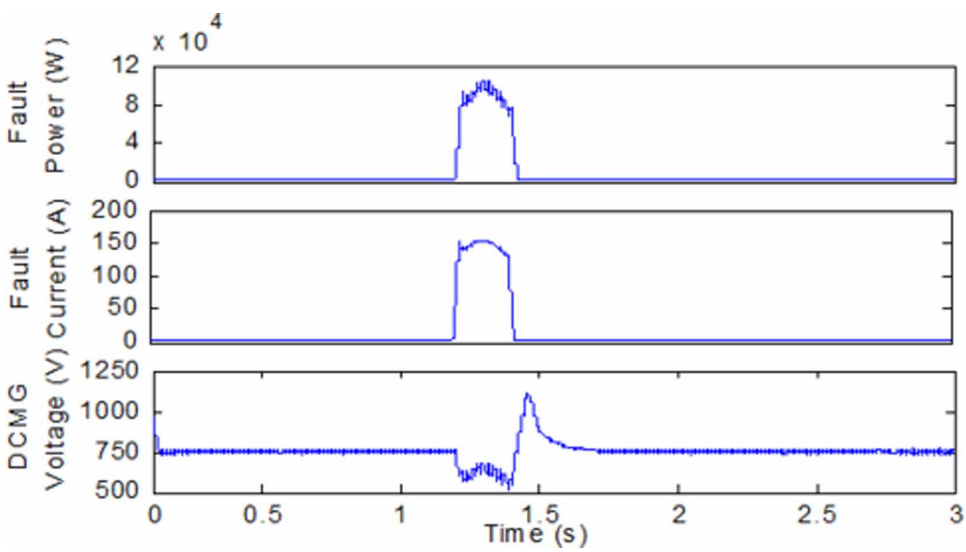

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Figure 7. Total load demand, total power generation, and power mismatch in the DCMG during fault, pre-fault, and post-fault

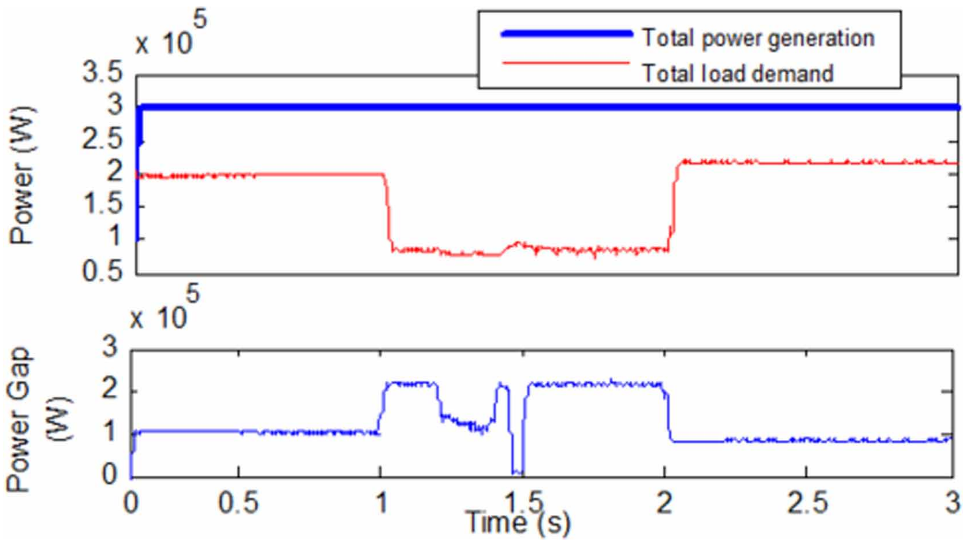
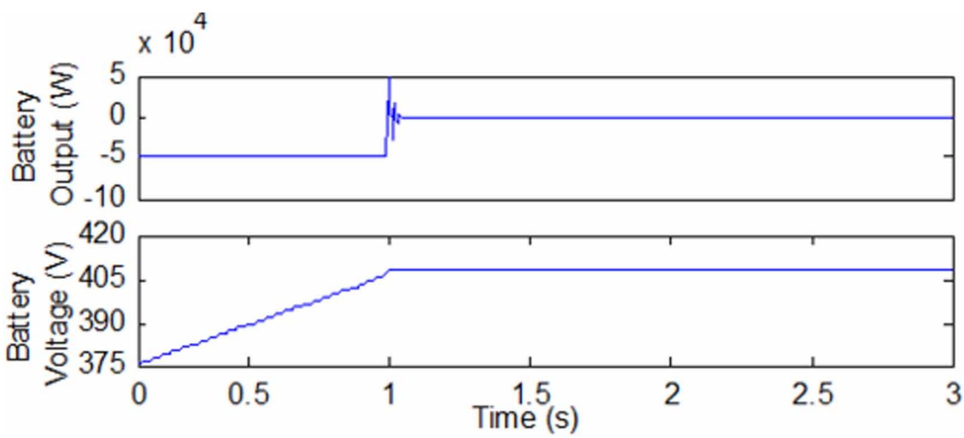


Figure 8. Output power and voltage of the battery during the fault and post-fault



Thus, the suggested control techniques for the operation of the hydrogen storage based smart DCMG control the power mismatch in the DCMG properly, under islanded mode, for the normal as well as fault cases. The DCMG voltage has also been maintained constant after clearing the fault (as before the fault), as shown in Figure 6.

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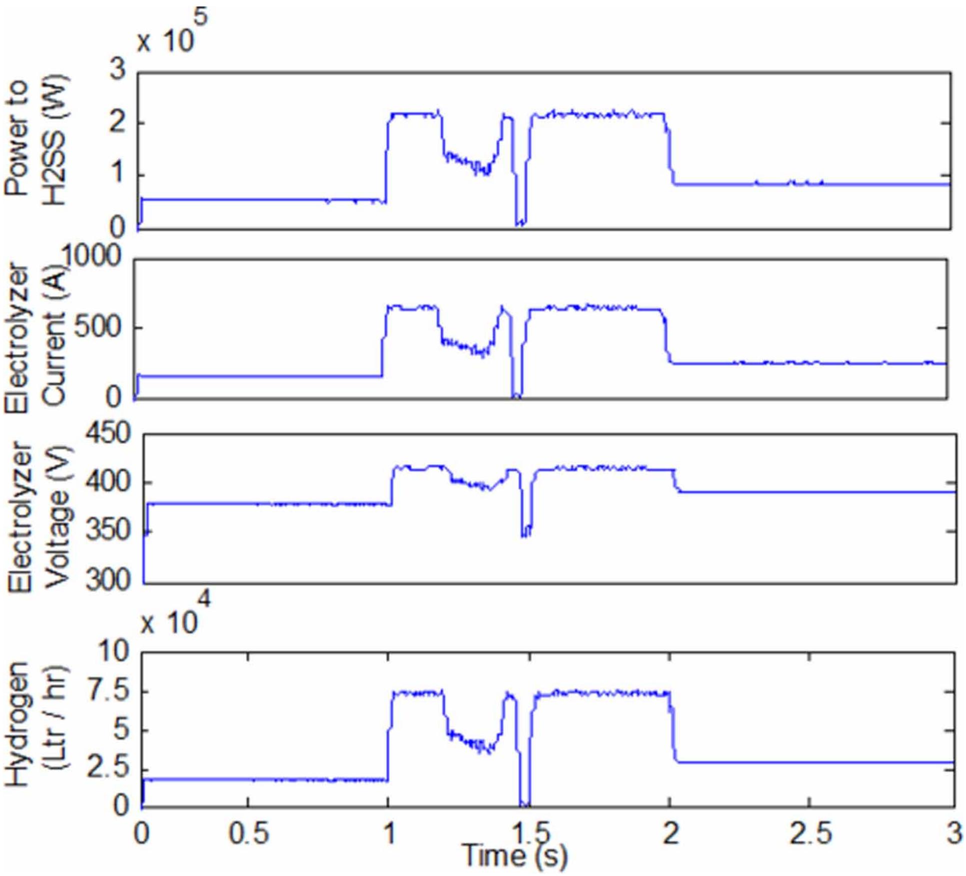
Figure 9. Surplus power stored in the hydrogen storage system, current and voltage of electrolyzer, and stored hydrogen amount during fault and post-fault



CONCLUSION

In this chapter, the control techniques for the operation of the hydrogen storage based smart DCMG are suggested and tested under islanded mode, for different operating conditions. The performance analysis of the hydrogen storage based smart DCMG along with the suggested control techniques, are presented to show its effectiveness and the robustness under various operating scenarios including the fault condition.

The simulation results provide that the suggested control techniques for the operation of the hydrogen storage based smart DCMG manage the power balance at the DCMG in islanded mode, by controlling the operation of the BESS up to its full charging capacity, and thereafter, to store the continuous

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generated surplus power into the hydrogen storage system, for the various operating scenarios. The suggested control techniques do not allow any adverse impacts on the loads and/or the generations during fault periods, except slight transients. As the dc fault is cleared, the DCMG voltage reaches to the steady state, and the DCMG operates under normal mode as in pre-fault conditions. The proposed hydrogen storage based smart DCMG along with the suggested control techniques, also offers the opportunity of the electrification of the remote rural areas.

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APPENDIX

The parameters used for the proposed DCMG have been mentioned in Table 2, which are considered from the works of Kumars (2015), Gyawali (2010), Kamel (2010), Xia (2013), and Mahmoud (2013).

Table 2. Main parameters of the operation of hydrogen storage based smart DCMG

DGs	Parameters	Values
Wind Turbine	***Wind Turbine:***	
	Number of units, N_{wt}	4
	Power of one unit, P_{rated} (kW)	50
	Diameter of rotor, D_b (m)	15
	Swept area, A (m^2)	177
	DFIG:	
	Rated output power, P_{rated} (kVA)	55
	Rated voltage, V_{rated} (V)	415
	Nominal frequency, f_n (Hz)	50
	Number of poles, p	6
	Turns ratio of stator to rotor, n	0.3806
	Resistance/phase of stator, R_s (pu)	0.0071
	Leakage reactance/phase of stator, X_{ls} (pu)	0.171
	Resistance/phase of rotor, R_r (pu)	0.005
	Leakage reactance/phase of rotor, X_{lr} (pu)	0.156
	Mutual reactance, X_m (pu)	2.9
Photovoltaic System	Maximum power, P_{max} (kW)	100
	Number of units in parallel, $N_{p,unit}$	4
	Maximum power of one unit, $P_{max,unit}$ (kW)	25.5
	Maximum voltage, V_{max} (V)	480
	Maximum current, i_{max} (A)	53.2
	Voltage across open circuit, V_{OC} (V)	552
	Current across short circuit, i_{sc} (A)	59.2
	Series modules in one stack, $N_{se,m}$	28
	Stacks connected in parallel, $N_{p,stack}$	13
	Series PV cells in one module, $N_{se,cell}$	36
Solid Oxide Fuel Cells	Rated power, P_{rated} (kW)	50
	Rated voltage, V_{rated} (V)	340
	Series cells in one stack, $N_{cell,fc}$	380
	Temperature, T (K)	1273
	Ideal potential, E_0 (V)	1.18
	Ratio (Hydrogen to Oxygen), r_{H_O}	1.145
	Ohmic losses, r (Ω)	0.126
	Peak power capacity, P_{peak} (kW)	90

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Table 2. Continued

DGs	Parameters	Values
Electrolyzer for Hydrogen Production	Rated power of a stack of electrolyzer, $P_{Elz,stack,rated}$ (kW)	40
	Series cells in one stack of electrolyzer, $N_{cell,Elz,stack}$	280
	Number of parallel stack in an electrolyzer, $N_{stacks,Elz}$	6
	Reversible voltage or thermodynamic cell voltage, $V_{res} = V_0$ (V)	1.22
	No load voltage of the electrolyzer, $V_{Elz,0}$ (V)	341.6
	Total rated power of the electrolyzer, $P_{Elz,rated}$ (kW)	240
	Area of one stack of electrolyzer, $A_{Elz,stack}$ (m^2)	0.25
	Over voltage of the electrolyzer per cell, V_1 (V)	0.185
	Electrolyzer temperature, T_{Elz} (^0C)	80
	Number of electrons transferred in each reaction, N_e	2
	Parameter of Ohmic resistance, r_1 (Ω-m^2)	8.05×10^{-5}
	Parameter of Ohmic resistance, r_2 ($\Omega\ m^2\ {}^0C$)	-2.5×10^{-5}
	Over voltage coefficient-1, m_1 (A^{-1}-m^2)	-1.002
	Over voltage coefficient-2, m_2 ($A^{-1}\ m^2\ {}^0C$)	8.424
	Over voltage coefficient-3, m_3 ($A^{-1}\ m^2\ {}^0C^2$)	247.3

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Chapter 6
Ocean Energy:
An Endless Source of Renewable Energy

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ABSTRACT

Until the middle of 20th century, there was a strong conviction that the next century would be the age of renewable and nuclear energy resources. However, at present, the whole world is dependent on fossil fuels to satisfy their energy need. Environmental pollution and global warming are the main issues associated with the use of fossil fuels for electricity generation. As per the report of US Energy Information IE Outlook 2016, coal, natural gas, and petroleum share nearly 67.2% of global electricity generation whereas renewable energy shares only 21.9%. This share is only one-fifth of the global electricity demand. According to the IEA 2016 Medium Term Renewable Energy Market Report, worldwide power production capacity of marine was only 539 MW in 2014, and to reach at a level of 640 MW, it will take 2021. The oceans cover about 70% of the Earth and acts as the largest thermal energy collector. A recent study reveals that global development capability of ocean energy is approximated to be 337 GW, and more than 885 TWH of electricity can be produced from this potential.

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INTRODUCTION

The world is facing a rapidly diminishing supply of fossil fuels causes the increasing rate of the generation of electricity using coal & fossil fuels. So that, natural sources are being utilized for the generation of electricity which will never end, named as renewable energy resources (RES). A renewable energy resource means a sustainable energy resource in which the energy received from the natural sources is termed as renewable energy. A sustainable energy research has mainly focused on the advancement of the sun oriented solar, wind, biomass and geothermal sources. Renewable energy resources are the fastest developing sources for the generation of electricity. In 2015, 24.5% of total electricity generation around the globe was shared by Renewable energy resources and predicted as 29.2% share till 2040 (Melikoglu, 2018).

Ocean energy is an endless renewable energy resource for the electricity generation all around the world. Oceans are the largest collector of the Sun's energy that is continuously renewed at all the times. Oceans covering 70% or more of the earth's surface. Oceans have an enormous amount of energy and this ocean energy formed due to the movement of water body in the oceans. Based on analysis and small-scale testing, the ocean energy resources for practical applications are ocean thermal, waves, tides, marine currents and salinity gradients to fulfil the need of power in all over the world at many times (Melikoglu, 2018).

Ocean energy has potential in terms of growth in the economy, security of supply and the decrease of CO_2 emissions. These economic and environmental benefits make a favorable base for the development of ocean energy around the globe. Ocean Energy sources have global potential such as tidal energy have 800 TWh per annum; osmotic energy have 2000 TWh per annum; wave energy has potential in the range of 8000 and 80,000 TWh per annum; and ocean thermal energy sources have potential in the range of 10,000 and 87,600 TWh per annum. The total potential of the electricity generation from the ocean energy is 20,000 TWh every year which is more than the worldwide electricity demand of 16,000 TWh every year (IEA-OES, 2021).

Ocean/marine energy technology was considered as too much costly source of clean energy, especially compared with already created products such as wind and solar.

Ocean Energy mainly found in five forms–

1. Tidal Energy

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2. Wave Energy
3. Ocean Thermal Energy
4. Marine/Ocean Current Energy
5. Osmotic Energy

In contrast to the above discussion, development of technology is the key driver to accelerate of the ocean energy. This paper provides a review on current advancement and status of ocean energy. The paper is prepared for providing information and all the topologies used in the field of ocean energy. Ocean energy technology can help to create economic growth of the countries in all over the world. The paper contains an overview of the main aspects and development of various technologies as well as supervision of ocean modelling and distribution challenges for implementation of these technologies. In section II, information related to various plants and technologies used will be discussed. Recent technologies helped with current energy & osmotic energy will be covered in the section III. In section IV and V, the focus will be given in the field of tidal energy and wave energy respectively. After that in section VI, various modelling of ocean thermal energy conversion (OTEC) plants will be given. Finally, the conclusion will be concluded from various analyses in the last section of this chapter.

HISTORY

Ocean, the monstrous source of energy, can produce two types of energy: thermal energy from the heat of sun and mechanical energy due to motion of water current. Ocean energy is being utilized in various forms over thousand years ago (Bache, 1924; Brauns, 2007; Khare, 2019; Nova Scotia Light and Power Company Limited, 1956; Pattle, 1954; Pecher & Kofoed, 2017; Ponta & Jacovkis, 2008; Rourke et al., 2010; Takahashi & Trenka, 1992; Vega, 2002). The first patent for wave energy devices was introduced in 19th century. A brief historical background of various ocean energy technologies is represented in this section.

Tidal Energy

Tidal energy is a form of ocean energy which utilizes the energy stored in water during the ascent and fall of tides. Firstly, the tidal energy was utilized

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in Europe to operate grain mills over 1000 years back and now it is utilized for the electric power generation (Melikoglu, 2018). The first study of tidal power plants was done by the US Federal Power Commission in 1924 (Bache, 1924). Later on, Nova Scotia Light and Power of Halifax commissioned two types of investigation on tidal power advancement in 1956. Further, a report was represented by the US and Canadian federal Govt. entitled 'Investigation of the International Passamaquoddy Tidal Power Project' in April 1961 (Nova Scotia Light and Power Company Limited, 1956).

In 1966, world's first tidal power generating station was established in La Rance, France with 240 MW installed capacity of 24 turbines that was (Melikoglu, 2018). The man who discovered this energy was M. Jannaschii. Later on, Jiangxia Tidal Power Station was constructed in 1985 with the installed capacity of 3.2 MW in China. Further, world's largest tidal power station was established in 2011 that was Sihwa Lake Tidal Power Station with the installed capacity of 254 MW in South Korea (Rourke et al., 2010).

India is the fourth largest country of electricity consumer after the United States, China and Russia. India has been looking at production of electricity by means of tidal power since 1980. The potential of tidal energy in India is 7 GW from the Gulf of Khambhat in Gujarat, 1200 MW of energy from the Gulf of Kutch in Gujarat and around 100 MW of energy from the Sundarbans in West Bengal. In India, first tidal energy plant present in the Gulf of Kutch, Gujarat with a power generation limit of 50 MW (Khare, 2019).

A list of 7 most important tidal power stations all around the world with their installed capacity is shown in table 1.

Table 1. History of tidal power station around the globe

S.No.	Tidal Power Station	Year	Country	Capacity (In MW)
1	Rance Tidal Power Station	1966	France	240
2	Kislaya Guba Tidal Power Station	1968	Russia	1.7
3	Jiangxia Tidal Power Station	1980	China	3.2
4	Annapolis Royal Generating Station	1984	Canada	20
5	Strangford Lough SeaGen	2008	United Kingdom	1.2
6	Sihwa Lake Tidal Power Station	2011	South Korea	254
7	MeyGen	2017	United Kingdom	6

(Khare, 2019)

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Wave Energy

Waves are generated in ocean due to the blow of strong wind on the surface. These waves carry the kinetic energy of wind and this energy can be converted into useful electrical energy by the application of suitable ocean turbine. The first patent on ocean energy was in 1799 by Girard & his son. Further, a wave energy device was invented by Bochaux-Praceique for the electricity generation in 1910. That wave energy device was the first oscillating water column type of wave energy device. Around 340 or more patents were done only in the United Kingdom from 1855 to 1973 on ocean energy (Pecher & Kofoed, 2017).

Wave energy research started in India in the year of 1983. World's first ocean wave energy plant was established in Vizhinjam, Thiruvananthapuram, Kerala in India in 1991 with a capacity of 150 kW using Oscillating Water Columns (OWC) technology. In 2003, the world's first ocean energy test facility was set up for the advancement of wave energy and tidal energy industries in the Orkney Islands, UK. European Marine Energy Centre (EMEC) is an only accredited tidal and wave test venue for marine sustainable energy sources in the world.

Various wave energy converters (WEC) are used for converting wave energy into electricity. Some of them are attenuator, point absorber, oscillating water columns and overtopping (Melikoglu, 2018). Wave farms were developed in the world using these wave energy conversion technologies. A list of top 10 wave power generating stations is represented in table 2.

Ocean Thermal Energy

Electric power can be produced by using ocean thermal energy which is defined as a difference in the temperature between surface water and water in around 1,000 m depth from the surface. In 1880, a formal concept to use the surface water of 24^0 to 30^0 C of the ocean to vaporize pressurized ammonia through a heat exchanger for example an evaporator and the cold water of 8^0 to 4^0 C temperature in 800-1000-meter depths from the surface of the ocean, to condense the ammonia vapor through a heat exchanger for example a condenser – was proposed by Jacques – Arsene d'Arsonval. D'Arsonaval concept was used in closed loop OTEC plants which contain ammonia (Vega, 2002).

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Table 2. History of wave energy station around the globe

S.No.	Wave Power Station	Year	Country	Capacity (in MW)	Type
1	Islay Limpet	2000	United Kingdom	0.5	Oscillating water column
2	Agucadoura Wave Farm	2008	Portugal	2.25	Surface following attenuator
3	Mutriku Breakwater Wave Plant	2009	Spain	0.3	Oscillating water column
4	SDE Sea Waves Power Plant	2009	Israel	0.04	Oscillating wave surge converter
5	Pico Wave Power Plant	2010	Portugal	0.4	Oscillating water column
6	Azura	2015	United States	0.02	Point Absorber
7	SINN Power wave energy converter	2015	Greece	0.02	Point absorber
8	Ada Foah Wave Farm	2016	Ghana	0.4	Point Absorber
9	Bolt Lifesaver	2016	United States	0.03	Point absorber
10	Orkney Wave Power Station	Proposed	United Kingdom	2.4	Oscillating wave surge converter

(Pecher & Kofoed, 2017)

In 1930, Georges Claude and another French inventor proposed a concept that the surface water was evaporated in a vacuum chamber and the subsequent steam passed through the turbine generator which was condensed through the deep water. Claude's cycle is alluded for an open cycle OTEC. The first representation of an OTEC power plant with the limit of 22 KW was built in Cuba in 1930 by Georges Claude. Another floating power plant with the limit of 2.2 MW was built in Brazil in 1935. Both OTEC power plants were not able to provide net power (Takahashi & Trenka, 1992).

Further development occurs in the OTEC technology in 1979, a pilot scale OTEC power plant was established in Hawaii by Natural Energy Laboratory of the Hawaii Authority (NELHA) with more than 50 KW of gross power. In 1981, an OTEC power plant was opened with 120 KW of gross power in Tokyo (Vega, 2002). Later on, in 1993, an open cycle OTEC power plant was constructed by NELHA with the net power of 103 KW. Later development in an OTEC technology in 2015, Makai Ocean Engineering launched the first closed-cycle OTEC power plant located in North Kona, Hawaii, USA by NELHA with the total annual power generating capacity of 100 KW (Takahashi & Trenka, 1992).

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This was the historical backdrop of the ocean energy which shows the successive development in the field of wave energy, tidal energy and ocean thermal energy. In the future as per the report of the International Energy Outlook (IEO) 2016, it is predicted that the renewable energy sources will share 29.2% in global electricity generation and 58.5% will be shared by fossil fuel till 2040. And in the European countries, the target is to reach 100 GW capacity installed from both wave energy and tidal energy by 2050 (Melikoglu, 2018).

OCEAN CURRENT ENERGY AND OSMOTIC ENERGY

Ocean energy, which is also referred as marine energy, is the energy due to the ocean waves, tides, salinity gradients and temperature distinction. Ocean energy is characterized as the source of kinetic energy that is developed due to the continuous motion of water. This kinetic energy is converted into useful electrical energy. Although, tidal energy, wave energy and ocean thermal energy are popular forms of the ocean energy still ocean current energy and osmotic energy are also accessible in present days with advancement in technology.

Ocean Current Energy Technologies

Ocean currents are generated due to the combined effect of environment temperature, wind speed, saltiness gradients and the pivot of the Earth. Ocean currents carries huge amount of water driven by the tides. (Melikoglu, 2018). Ocean currents might be the appropriate way to extract the dynamic energy of ocean currents and to put a turbine to get electrical energy in output such as in the case of wind energy.

The potential to generate electricity form ocean currents is estimated to be 5 TW (Melikoglu, 2018). There are various kinds of an open-flow device which can be utilized in the ocean current technology. The more technical designs are based on wind turbine rotors and are used to achieve sufficient cost-viability and dependability for a massive ocean current energy system. These open flow turbines refer as the water current turbines. There are mainly two sorts of water current turbines axial-flow horizontal-axis propellers and cross-flow Darrius rotors. The fig. 1 represents the mechanism to extract the power from ocean current energy.

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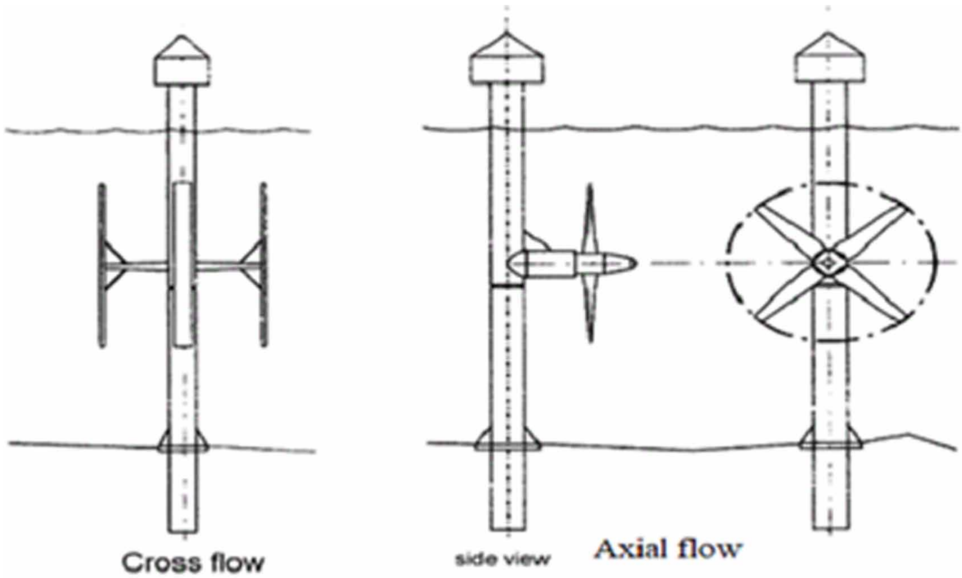
Figure 1. Marine current power
Source: Melikoglu, 2018



For supporting water current turbines, both types of rotors can be joined by any of the three techniques: floating moored frameworks, ocean-bed mounted frameworks and middle frameworks (Melikoglu, 2018).

Osmotic Energy

Osmotic energy is also known as salinity inclination energy or blue energy. Salinity inclination energy is accessible from the distinction in the salt concentration between fresh water and salt water. In rivers, fresh water mixes with salt water. The energy associated with the saltiness gradients can be utilized to generate electricity using reverse electro dialysis (RED) and pressure retarded osmosis (PRO) technologies. The two processes rely upon the osmosis with membranes and the waste product is brackish water (Melikoglu, 2018).

In 1954, Pattle proposed that there was a wellspring of power when a river blends in with an ocean, because of the osmotic pressure (Norway's Osmotic Power, 2013). Further, the method of producing electric power by pressure retarded osmosis (PRO) technology was introduced by Prof. Sidney Loeb in 1973 at the Ben-Gurion University of the Negev, Beersheba in Israel. Prof.

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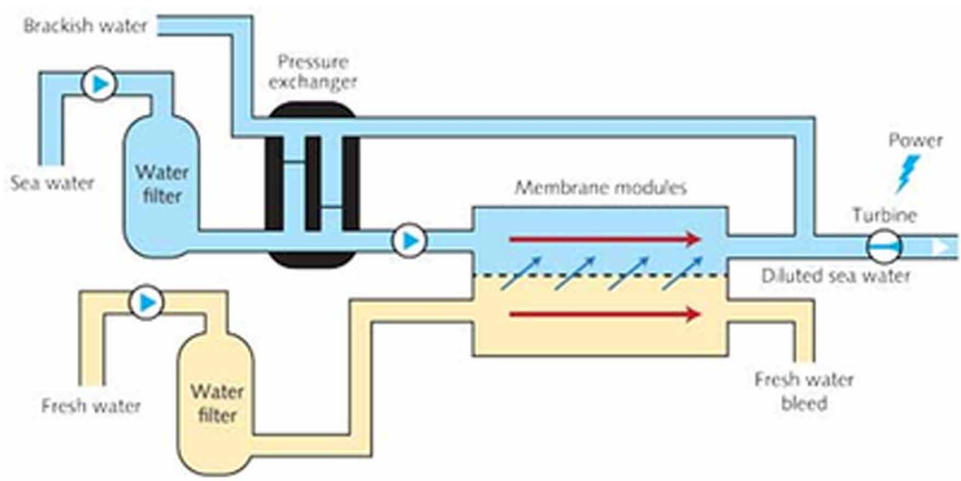
Sidney Loeb observed that the Jordan River was streaming into the Dead Sea and he needed to utilize the energy of blending of the two liquid arrangements. In Braun's article, Prof. Sidney Loeb expresses that the solutions of fresh water and salt water were separated by a membrane. Fresh water moves in a semipermeable film and in the resulting, an osmotic pressure creates the difference between both the solutions. Thereafter, he developed a technique for generating electric power from a reverse electro dialysis (RED) technology in 1977 (The world's first osmotic power plant from Statkraft, n.d.). The fig. 2 represents the power generation process using osmotic energy.

Figure 2. Osmotic power
Source: Le et al., 2017



The first technique to utilize the saltiness inclination energy is pressure retarded osmosis (PRO). In this, the ocean water is pumped into a pressure chamber through a membrane at a pressure lower than the distinction between the pressures of salt water and fresh water. As the result of differences in pressure, a turbine is being supplied by kinetic energy (The world's first osmotic power plant from Statkraft, n.d.). World's first PRO technology based osmotic power plant was Statkraft Osmotic Power Plant having 10 kW power generations capacity per year. Statkraft Osmotic Power Plant was opened by Princess Mette-Marit of Norway on November 24, 2009 (Khan et al., 2017). In January 2014, this plant was closed due to governmental and financial issues. The fig. 3 below shows the plant location and technology behind the electricity generation.

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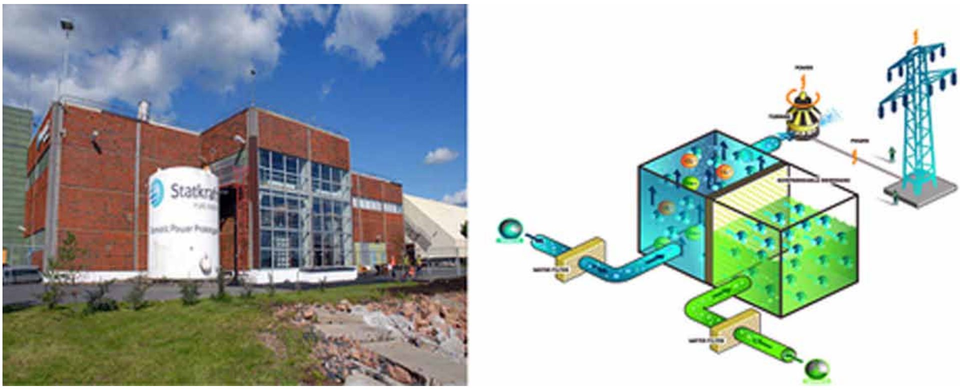
Figure 3. Statkraft Osmotic Power Plant & Its Technology
Source: Phuoc & Dong, 2019



The second technique is being studied the reversed electro dialysis (RED) technology, which is essential for the creation of a salt battery. The principle of reversed electro dialysis was invented in the 1950. This technique was described by Weinstein and Leitz as substituting anion and cation exchange membranes can be utilized to produce electric power from the sea water. Saltiness inclination power generation happens in different countries like Japan, Israel, and the United States. It is the salinity gradient power technology (The world's first osmotic power plant from Statkraft, n.d.).

TIDAL ENERGY

Tidal energy is one of the most significant form of the ocean energy which is generated due to the centrifugal and gravitational forces between the moon and the sun with respect to the earth. A tide rises and falls in the ocean due to the gravitational force of the moon and the sun on the earth, whereas the centrifugal force is delivered by the turn of the moon and the earth with each other (Charlier & Finkl, 2009). The gravitational force and centrifugal force act together to maintain the equilibrium between the earth and the moon. A bulge of water is formed by the gravitational pull force of the moon, which is much greater on the side of the earth facing the moon. A centrifugal force produced the turn of the earth–moon system which causes another water swell on the side of the earth far away from the moon (Shaikh, 2011). The effect of moon for generation of tides is represented in fig. 4.

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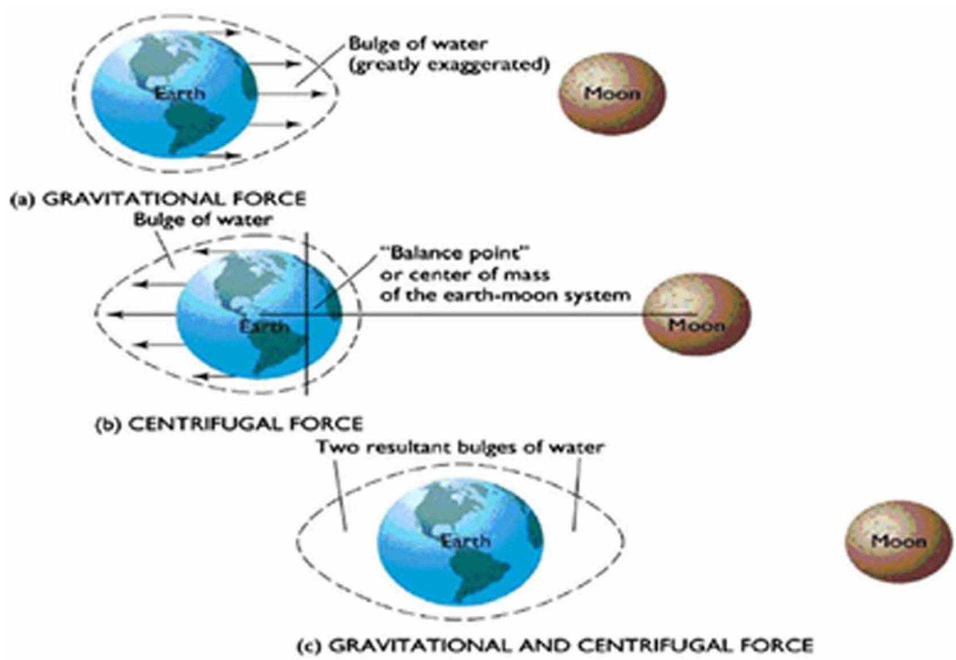
Tidal energy is also a form of hydro energy which can be obtained by two different ways - the tidal current energy to rotate the turbine to create electric power and the tidal potential energy between the elevated/ high tide and low tide (Charlier & Finkl, 2009). Tidal energy was used firstly in the Europe to operate grain mills over 1000 years ago. World's first and biggest tidal energy plant was established in La Rance, France in 1966, having 240 MW installed capacity of 24 turbines. Then after Sihwa Lake Tidal Power Station was installed with a capacity of 254 MW in South Korea (Charlier & Finkl, 2009; Shaikh, 2011). Sihwa Lake Tidal Power Station is the largest power producing tidal energy plant in the world. The global tidal energy potential is estimated about 500 to 1000 TWh every year (Blunden & Bahaj, 2007).

Figure 4. Effect of the moon on tidal energy
Source: Greaves & Iglesias, 2017



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Methods of Tidal Energy

Tidal energy is the kinetic energy generated from the movement of water due the tides. Tides are more predictable than wind and sun. There are basically four kinds of tidal energy technologies used to generate electricity (Greaves & Iglesias, 2017).

1. Tidal Stream Generator
2. Tidal Barrage
3. Tidal Lagoon
4. Dynamic Tidal Power.

Tidal Stream Generator

Tidal stream generator is also called a tidal energy converter (TEC). It is a device that converts the kinetic energy of moving energy into electrical energy. Tidal stream or tidal current which are generated because of tides can be converted directly into the electrical power by using tidal energy converting devices or turbines without actually constructing any dam or barrage. Tidal stream generators, tidal stream turbines and tidal energy converters are an emerging technology used as tidal current turbines (Fraenkel, 2007).

Tidal current turbine consists a number of sharp blades mounted on a rotor, a gearbox and an electric generator. The rotor is associated with a gearbox which is utilized for converting the rotational speed of the rotor into the ideal speed of the electric generator (Pecher & Kofoed, 2017). At the point when the water current passes through the blades, it causes the revolution of the rotor and hence the generator to generate electric energy. The generated electricity is transmitted to the load points by underwater cables. Tidal current turbines can be categorized as horizontal-axis turbines and vertical-axis turbines. Sharp blades of the horizontal-axis turbines rotate about horizontal axis which is corresponding to the direction of the progression of water. Fig. 5 shows the generation of electricity from tidal stream generator and fig. 6 represents the vertical and horizontal axes stream turbines. In the vertical-axis turbines, sharp blades rotate about vertical axis, which is opposite to the direction of the progression of water (Chowdhury et al., 2021).

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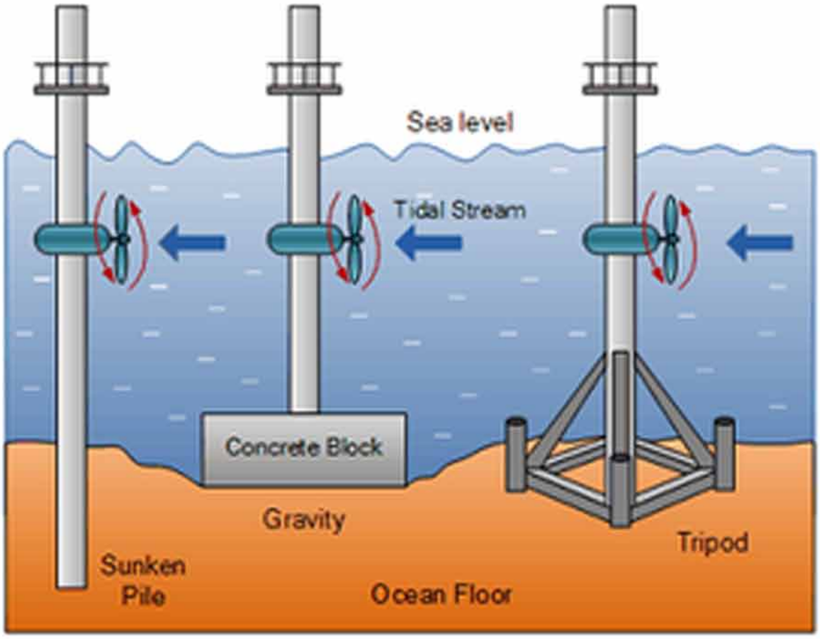
Figure 5. Tidal stream generator
Source: Etemadi et al., 2011



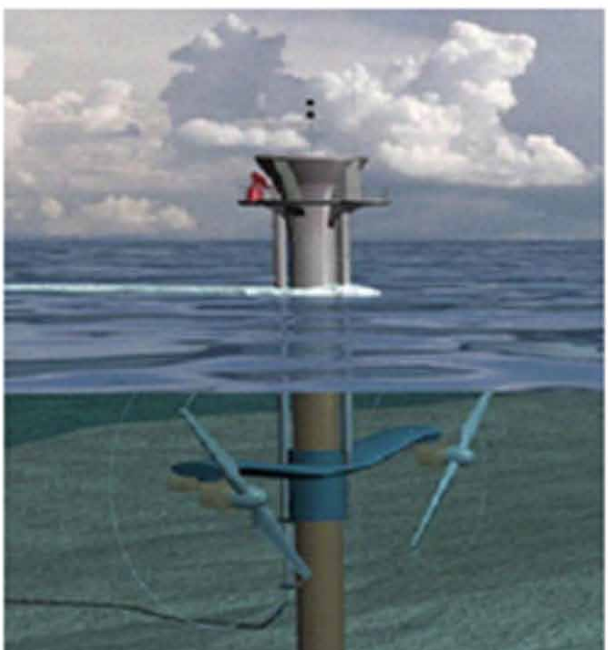


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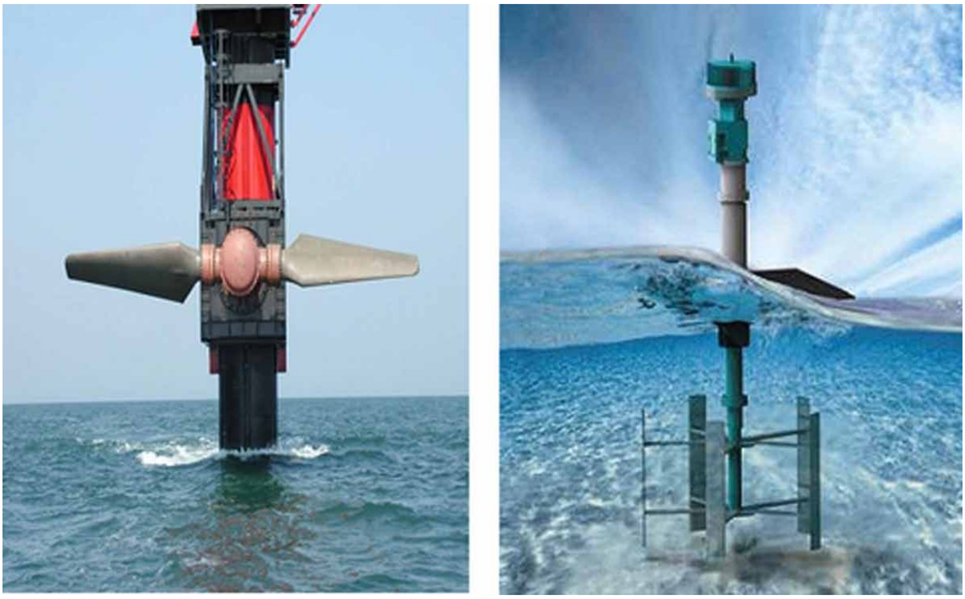
Figure 6. Tidal current / stream turbines (A) Horizontal-axis turbine (B) Vertical-axis turbine
Source: Etemadi et al., 2011



Tidal stream turbines are designed much similar like to the wind turbines. In tidal energy, the power (P) is proportional to the square of the water head distinction (H^2) among the upstream and downstream side of plan surface area (A). The power taken by the turbine is given as:

$$P = \frac{dC_p A V^3}{2}$$

Where, P = power in Watt (W)
d = density of water in Kg. /m^3
C_p= power coefficient
A = cross – sectional area of turbine in m^2
V = current velocity in m/seconds

In 2007, world's first tidal power station using tidal stream generators was established at Strangford Lough in Northern Ireland. Turbines of the stream generator are installed in a slender strait between the Strangford Lough inlet and the Irish Sea. In the modern period, Strangford Lough was known as Loch

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Cuan in Irish which is referred as ocean inlet of bays or havens. The tides can move up to 4 meters or 13 feet per second in the ocean (Rourke et al., 2010).

Tidal Barrage

Tidal barrage contains potential energy of the tides. Tidal barrage has potential to generate electricity with the help of formation of a dam or barrage in a basin which utilizes the energy between high and low tides. Electricity production by using a tidal barrage is mature, reliable and the principle is much similar to the principle of hydroelectric production. In tidal barrage technology, the tidal current flow in both directions. In the world, there are several tidal power plants produce electricity by using tidal barrage technique. For example - La Rance tidal power plant in France, Sihwa Lake Tidal Power Station in South Korea, tidal power plant in Annapolis Royal in Nova Scotia Canada, Kislaya Guba power plant in Russia, Jiangxia tidal power plant in China etc. (Copping, 2020). Tidal barrage consists turbines which are bi-directional. Tidal barrage method can be classified into two categories: single basin tidal barrage system and double basin tidal barrage system (Greaves & Iglesias, 2017).

Tidal Lagoons

A large quantity of estuaries is located in the United Kingdom (UK) having the excessive tidal range and sturdy tidal currents. In the UK, tidal range (lagoons) has estimated potential as 25 TWh/year. Tidal lagoons are the built structure which consists of the number of turbines that contains the potential energy of the tides. Tidal lagoons method is similar to the tidal barrage method except that the location is artificial. Tidal lagoons are independent tidal barrage so that, these lagoons do no longer block the progression of water of the stream. In tidal lagoons, the barrage structure creates a hydrostatic head contrast among flood tides and ebb tides. These independent barrages are built on high level tides estuary land. Tidal lagoons use a circular shape of a river, not fully the estuary (Hinson, 2018; Waters & Aggidis, 2016).

United Kingdom is fortunate enough with the huge sustainable energy resources alternatives and the largest potential for tidal energy in the world. In the UK, the Swansea Bay is being an aspect of the Severn Estuary with the largest tidal range (10.5 m). Tidal Lagoon Swansea Bay is the first tidal power station, which is generating 320 MW electricity. In fig. 7, the location and satellite view of Swansea Bay is shown. Kaplan Bulb turbines, each of

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16 MW capacity, are used in this power plant. There are two types of lagoon structures: offshore and onshore. An offshore lagoon involves a round dam in which the power is transmitted to shore via the links below the seabed. In an onshore lagoon, the dam frames a horseshoe shaped structure in which the rest of the circle is created of the shoreline that is joined with it (Hinson, 2018).

Figure 7. Tidal lagoon Swansea Bay
Source: Waters & Aggidis, 2016

At high tide, the sluice gates are closed till the tides create a hydrostatic head throughout the barrage. At this point, the sluice gates are opened and water inside the lagoon is allowed to circulate through the turbines for producing electricity. It is ebb generation scheme. The turbines are able to accomplish a very high effectiveness of 93% during the ebb cycle. During the flood cycle, the productivity drops to 75%. Pumping is an extra method is applied in which utilizing the turbines in opposite as pumps to rise a hydrostatic head distinction among the lagoon basin and the ocean (Waters & Aggidis, 2016). The power produced by lagoon is abundantly associated with the head distinction among the lagoon basin and the ocean. The potential power is–

$$E = \frac{Adgh^2}{2}$$

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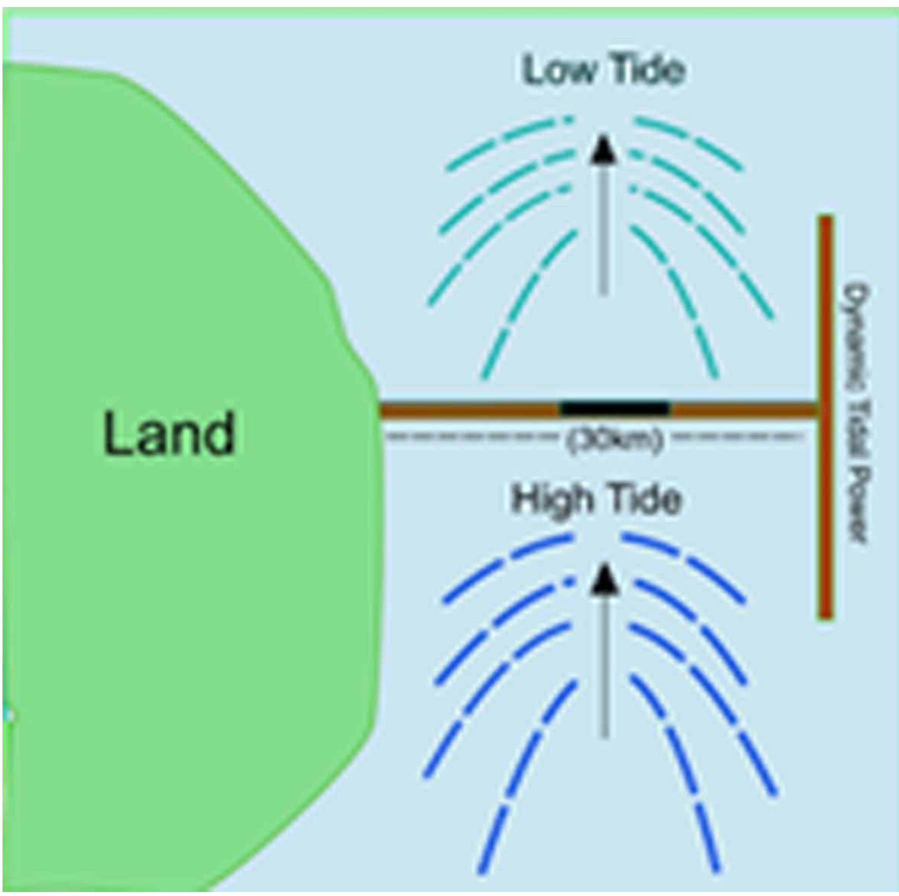
Where, h = comparison in the head between the lagoon basin and the ocean
d = density of water
A = area of the barrage basin.

Dynamic Tidal Power

Dynamic tidal power (DTP) is another and unexperienced technique for tidal power production. This technology includes making an extended dam like construction from the coast with a hindrance at the far end forming an enormous 'T' shape which is straight out into the ocean as shown in fig. 8. This T-dam might encroach with coast parallel tidal waves contain effective hydraulic currents (Hulsbergen et al., 2008).

Figure 8. Dynamic tidal power plant
Source: Pelc & Fujita, 2002



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The above picture shows a perspective on a DTP dam. A DTP dam is extended nearly 30 km that is opposite to the coast and straight out into the ocean. The dam prevents the tides from horizontally speeding up. The primary tidal movement runs parallel to the coast and causes the entire mass of the ocean to accelerate in one direction before returning the opposite way later in the day. A DTP is long sufficiently for horizontal tidal motion which creates a water stage differences over the two sides of the dam (Fox et al., 2018; Pelc & Fujita, 2002).

Advantages and Disadvantages of Tidal Energy

Advantages –

1. Being green source of energy, tidal energy is environment friendly.
2. Tidal energy is predictable renewable energy source as compared to solar and wind power.
3. Operational and maintenance costs of tidal power plants are low.

Disadvantages –

1. High construction cost of barrages and selected sites of large basin area.
2. Highly affects the ecosystem of the ocean.
3. The continuity of power supply is not available.

WAVE ENERGY

Wave energy is clean, periodic and promising renewable energy technology. Ocean waves are produced by blowing of sturdy wind over the surface of the ocean. These waves hold the huge potential for electricity generation. Wave energy is produced because of the kinetic energy of wind and this only energy is available to get converted into electrical energy (Pecher & Kofoed, 2017). The air blows due to the temperature difference, created by heat energy of sun. The height of the waves varies with the speed of the wind. Hence, the size of ocean wave depends on three factors–

1. Strength of the wind
2. Time all through which the wind blows

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3. Distance across which the wind blows

By capturing the wind power in form of wave energy, the wave power is transformed into mechanical power and then into electrical power. It can be stated that the wave power is concentrated type of the solar power. According to the World Energy Council, worldwide wave energy potential is provided up to 2 TW of electricity (IEA-OES, 2021).

Ocean wave power generation ability is measured as energy density per wave peak (kW/m). The generation of the ocean waves is a non-linear process. The behavior of the ocean is represented by an energy density spectrum $S(f,\theta)$. The energy density spectrum is proportional to the variance of the floor elevation in phrases of frequency and direction. The parameters of the density spectrum are wave height, time period and direction. Significant height of wave is used which is considered as the average of the biggest one third of the waves. Significant wave height can be calculated as…

Where m_0 is the zeroth spectral momentum.

$$H_s = 4 \times m_0^{0.5} \tag{1}$$

$$m_n = \int\int f^n S\left(f,\theta\right) df d\theta \tag{2}$$

Where m_n is the nth momentum of the directional power distribution.

The energy time period relies upon the lower frequency band which includes maximum energy. The energy time period is expressed as

$$T_e = \frac{m_{-1}}{m_0} \tag{3}$$

The peak period is the inverse of the peak frequency which can be given as–

$$T_p = \frac{1}{f_p} \tag{4}$$

By using of these parameters, the equation of wave power for irregular waves can be given as–

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$$P_x = \rho g \int \int C_{gx} S\left(f,\theta\right) df d\theta \tag{5}$$

$$P_y = \rho g \int \int C_{gy} S\left(f,\theta\right) df d\theta \tag{6}$$

In the equation (5) and (6), *S (f, θ)* is the density spectrum across the longitude system on *x* – plane and the latitude system on *y* – plane respectively (Melikoglu, 2018). Here,

Water density, $\rho = 1.025\ g/m^3$
Gravitational acceleration, $g = 9.81\ m/s^2$
Group speed in deep water, $C_g = g/(4\pi f)$

Total wave power can be given as–

$$P = \left(P_x^{\ 2} + P_y^{\ 2}\right)^{½} \tag{7}$$

Now, the total wave power can be computed as

$$P = \frac{\rho g^2 m_{-1}}{4\pi} \tag{8}$$

Wave power can be expressed in terms of H_s and T_e as follows:

$$P = \frac{\rho g^2 H_s^{\ 2} T_e}{64\ \pi} \tag{9}$$

The final equation of wave power in terms of KW/m can be obtained by expressing H_s in meters and T_e in seconds.
So that

$$P = 0.5 H_s^{\ 2} T_e \left(kW\ /\ m\right) \tag{10}$$

The above equation (10) is the expression for wave energy or wave power. By putting the value of H_s and T_e, we can calculate the amount of wave power in kW/m (Melikoglu, 2018).

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Usually, wave statistics resources take measures of the wave height, wave time period and wave direction (Nova Scotia Light and Power Company Limited, 1956). One of the widely recognized wave statistics resources is the Summary of Synoptic Meteorological Observations (SSMO). The human's calculating error is one of the main disadvantages of the observation method. The setup of buoys is also able to take wave measures. The National Data Buoy Center (NDBC) is estimating buoys in various countries in the world. Any other technique of wave measures is the utilization of PC models. Wave Information Study (WIS) is a model developed by engineers of the US Army Corps. This model consists of software which provides wave measures depending upon the atmospheric pressure of the ocean surface winds. WIS contains recorded data set for a time of 20 years.

Wave Energy Conversion Devices

Ocean wave energy conversion basically comprises two stages: wave power is changed over into mechanical power firstly and then electrical power can be generated from mechanical power. Wave energy converters are employed for the conversion of wave power. Wave energy converters may be utilized in offshore or near-shore locations. The mechanism of wave energy converter is to drive a hydraulic engine which is associated with an electric generator. A wave energy converter converts energy from waves into a high pressure hydraulic which can be utilized to drive a hydraulic engine. This type of mechanism is called hydraulic power take off mechanism (Drew et al., 2009; Hammar et al., 2012).

Various wave energy converters have been developed in 20^{th} century. Presently, more than 1000 wave energy technologies for wave energy converters have been patented in all around the world (European Marine Energy Centre Ltd, n.d.). There are mainly four sorts of wave energy conversion devices known as wave energy converters (WEC) and these are: attenuators, point absorbers, oscillating water columns and overtopping devices.

Attenuator

The attenuator is a floating device operated corresponding to the direction of the wave. Multi-segments of the device are connected with a hydraulic motor. An attenuator takes energy from the wave when both arms of an attenuator are in motion with the passing wave. The movement of an attenuator can be in horizontal as well as in vertical. Pelamis is an attenuator type wave energy converter (Rhinefrank et al., 2006). The attenuator is shown in fig. 9 below:

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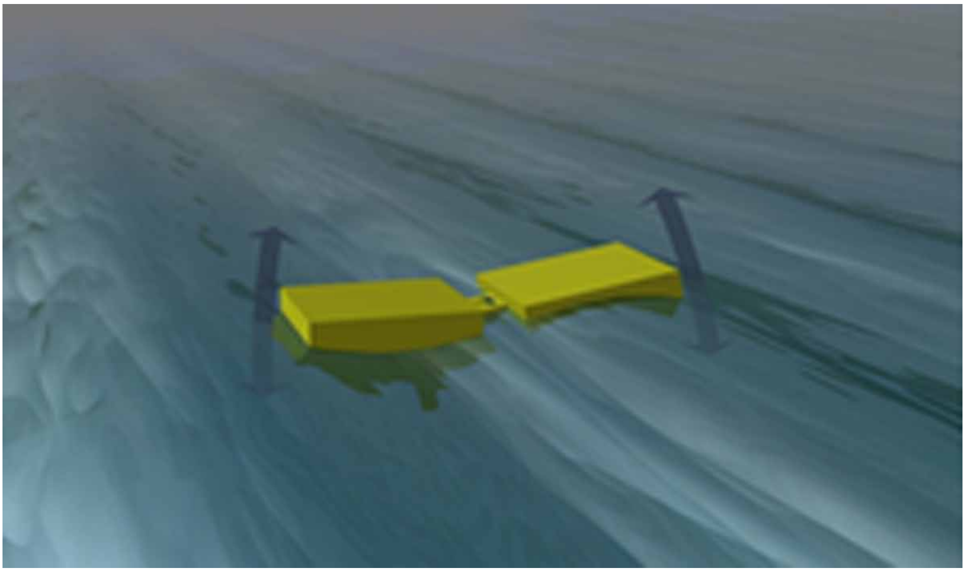
Figure 9. Attenuator
Source: European Marine Energy Centre Ltd, n.d.



Point Absorber

The point absorber is a floating buoy that is capable to soak up power from the motion of waves through its movement. Generally, point absorber devices are installed in large oceans. A point absorber can generate electricity with the use of the ascent and fall of the wave. The point absorber can move in vertical direction only as shown in fig. 10. Aqua Buoy, Power Buoy, Archimedes wave swing are some point absorber type of wave energy converters (European Marine Energy Centre Ltd, n.d.).

Oscillating Water Columns

An oscillating water column (OWC) or terminator is a wave energy conversion device comprises of the air chamber above the surface of the ocean. At the point when the wave enters the chamber, an OWC device develops the rise and fall the water level. It is also responsible for the increasing and decreasing the air pressure inside the cavity as shown in fig. 11. This compressed air passes on the turbine to generate electricity (Zhu et al., 2020).

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Figure 10. Point absorber
Source: European Marine Energy Centre Ltd, n.d.

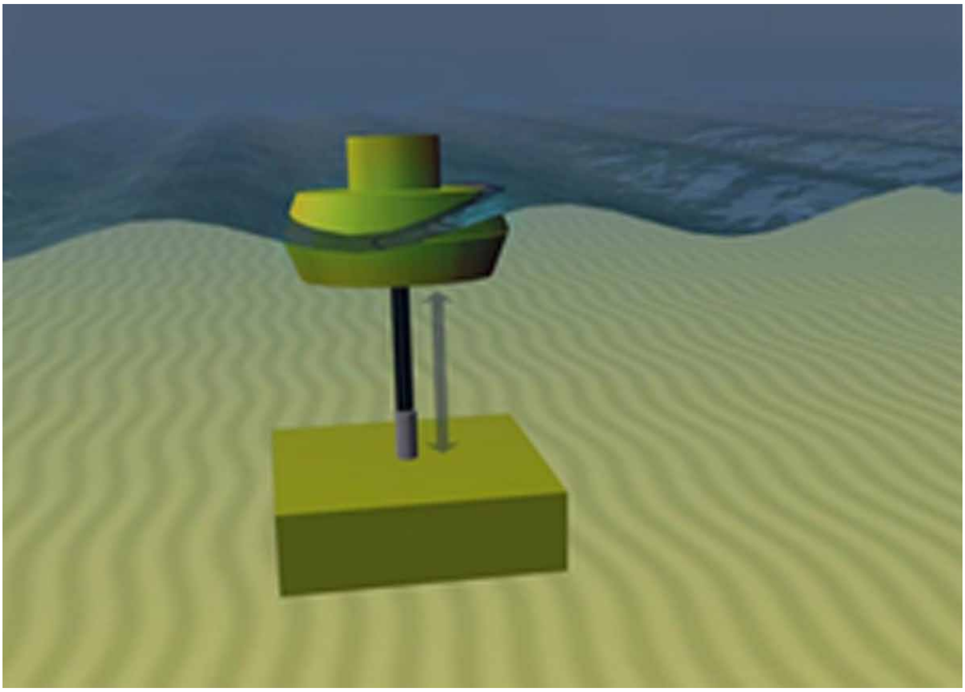
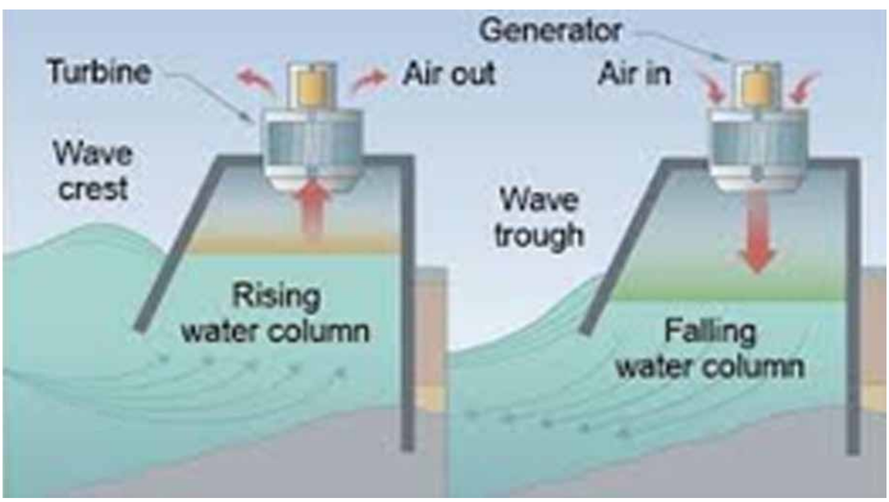


Figure 11. Oscillating water columns
Source: Zhu et al., 2020



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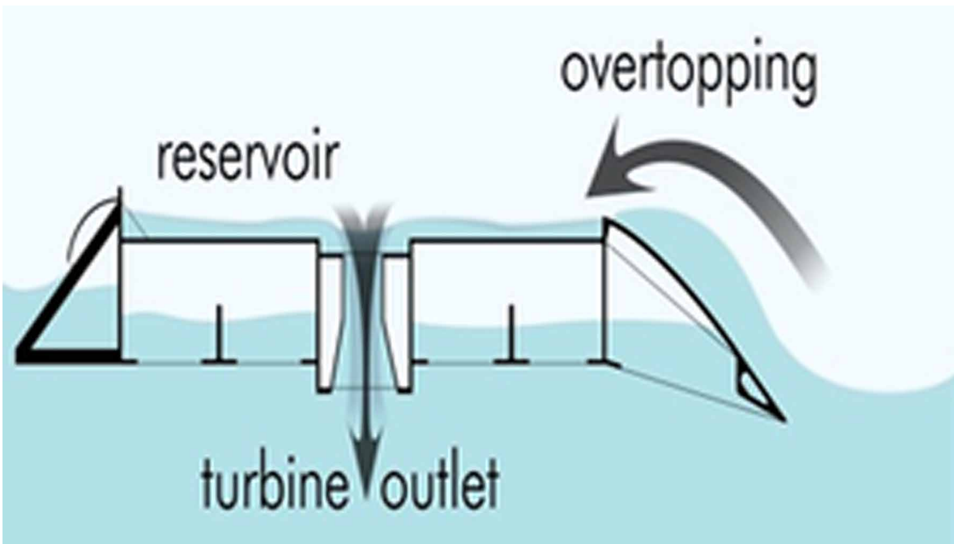
Overtopping

Overtopping wave energy conversion technique consists of a barrier through which wave overtops and the overtopped water as a wave comes in the reservoir as shown in fig. 12. Then, this collected water in the reservoir is returned back into the ocean through the conventional low-head turbine that is coupled to an electrical generator. Hence, the electric power can be obtained by using of overtopping wave energy converters. Wave Dragon, Tapchan and Wave Plane are overtopping type of wave energy converters (Van der Meer et al., 2018).

Figure 12. Overtopping
Source: Van der Meer et al., 2018



Advantages and Disadvantages of Wave Energy

Advantages

1. Wave energy does not pollute the environment by production of greenhouse gases. Hence, the wave energy is clean and green energy.
2. Worldwide electricity production potential is estimated up to 2 TW from the ocean waves. The wave energy is a reliable source of energy.

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3. Wave energy use no fuel cost and operating cost of the wave energy devices is also less.
4. Wave energy density along to the shore is approximately 30 – 40 kW/m. The ocean wave can generate huge amount of electricity.
5. There is no requirement of any land for establishing a wave energy power plant.

Disadvantages

1. Wave energy is a less feasible source of energy.
2. Wind power is extremely depending upon the wavelength such as wave velocity, wavelength and the water density. Wavelength changes with the change in the speed of wind.
3. The production cost of electricity using wave energy is high due to costly infrastructure and machineries.

OCEAN THERMAL ENERGY

The ocean thermal energy is existing since the sun and earth are existing. Ocean thermal energy is developed due to the temperature difference between the surface water and the water at 1,000 m depth. Surface water gets heated from solar energy while the water at a depth of 1000 m remains cold due to the motion of waves and high latitudes (Melikoglu, 2018). The resource potential for OTEC is considered to be much larger than for other ocean energy forms. Up to 88,000 TWh/yr. of power could be generated from Ocean Thermal Energy Conversion (OTEC) without affecting the ocean's thermal structure (Bedard et al., 2010; Masutani & Takahashi, 2001). The generation of electrical energy from ocean thermal energy is done by OTEC.

Ocean Thermal Energy Conversion

Ocean Thermal Energy Conversion (OTEC) is a process which includes taking energy from the distinction in temperature between the shallow water and the deep water of the ocean by using a heat engine. The surface water's temperature of the tropical oceans is about 24 ^{0}C to 30 ^{0}C and the cold water is found at 1,000 m depth with the temperature ranging from 8 ^{0}C to 4 ^{0}C. Ocean thermal energy conversion system operates when a minimum temperature

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distinction (ΔT) between the cold deep water and the warm surface water is nearly 20 ^{0}C. OTEC provides water without salts and minerals which is known as desalinated water. The output power of the turbine generator fluctuates with the square of ΔT. The thermal efficiency of the OTEC power plant is very low due to the difficulty and expensive cost of the extraction of energy (Vega, 2002).

An OTEC power plant contains several components such as a heat engine, steam turbine, condenser and electric generator etc. There are two reservoir acts as a heat source and heat sink for the heat engine. A heat engine is positioned between the high temperature and the low temperature reservoir (Takahashi & Trenka, 1992). The energy is generated from the heat engine and with the help of steam turbine, converted into kinetic energy. Surface water of the ocean forms steams to drive a turbine. A turbine is coupled to an electric generator which is responsible for the electricity generation. Then, cold deep water of the ocean is brought to the surface by pipes and it can be used to condense the steam (Panchal & Bell, 1987; Uehara et al., 1990).

The factors that affects the site selection for OTEC power plant are:

1. The minimum water temperature difference must be of 20 ^{0}C.
2. The distance from the thermal resources to the shore.
3. Type of facility like near shore and free floating.
4. Potential of deep ocean water applications.
5. Impacts of the environment at the location.
6. Mooring and floating system in the bottom of the ocean.

OTEC power plants can be constructed on both onshore and offshore floating systems. Floating systems do not require any valuable land near the ocean (Takahashi & Trenka, 1992). The OTEC plant can be classified as:

1. Closed Cycle OTEC Plant
2. Open Cycle OTEC Plant
3. Hybrid Cycle OTEC Plant.

Closed Cycle OTEC Plant

For electricity production, the ocean thermal energy conversion closed cycle idea was proposed by Jacques Arsene D'Arsonval in 1880. In the closed cycle OTEC concept, fluid of low boiling point, for example, ammonia is used as

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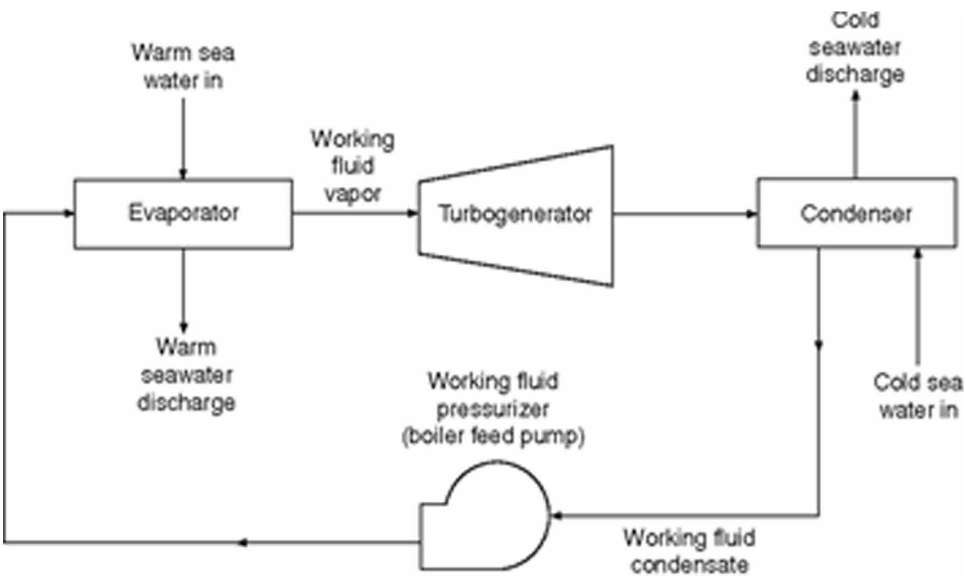
an operating fluid. This ammonia flows between two heat exchangers i.e. evaporator and condenser (Uehara et al., 1990). First of all, warm surface water of the ocean uses to vaporize ammonia through the first heat exchanger i.e. evaporator in the closed cycle OTEC system. The resulting vapor is used to rotate the turbine that is coupled with an electric generator which is responsible for the generation of electricity. After the vapor rotates turbine, the vapor is being condensed using cold deep water of ocean through the second heat exchanger i.e. condenser. Then, ammonia vapor is pumped back through an evaporator for repetition of the cycle (Uehara et al., 1990). The basic block diagram of closed cycle OTEC plant is shown in fig. 13.

Figure 13. Closed cycle OTEC process
Source: Uehara et al., 1990



The first closed cycle OTEC power plant having 100 KW of power generating capacity was launched in North Kona, Hawaii, USA by the Natural Energy Laboratory of Hawaii Authority (NELHA) in 2015 (Cavanagh et al., 1993; Renewable energy statistics 2020, 2020).

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Open Cycle OTEC Plant

Ocean water can be used as an operating fluid for the production of power. In 1930, Georges Claude proposed a concept based on the open cycle OTEC process. Surface water of the ocean is used as an operating fluid in the open cycle OTEC process that could be a low-pressure steam. In an open cycle OTEC process, surface water of the ocean is flashed into the vacuum chamber via an evaporator. Then, low pressure steam is allowed through the turbine that is coupled with an electric generator which generates electricity. Later, the steam is condensed using cold deep water of the ocean through a condenser. In this cycle, the steam is not pumped back through an evaporator. So that, the open cycle OTEC process is also referred to as Claude's cycle (Takahashi & Trenka, 1992).

In 1984, the Solar Energy Research Institute (now known as the National Renewable Energy Laboratory) developed a vertical-spout evaporator to convert warm seawater into low-pressure steam for open-cycle plants. Conversion efficiencies were as high as 97% for seawater-to-steam conversion (overall steam production would only be a few percent of the incoming water). In May 1993, an open-cycle OTEC plant at Keahole Point, Hawaii, produced close to 80 kW of electricity during a net power-producing experiment. The basic block diagram of open cycle OTEC plant is shown in fig. 14.

Claude's cycle was performed with a small land-based power plant in Cuba in the year of 1930. Further, a floating power plant of 2.2 MW was designed in Rio de Janeiro, Brazil by Claude. But both plants didn't provide a net output power (Vega, 2002).

Hybrid Cycle OTEC Plant

Hybrid cycle is the combination of both the closed and open cycle system. In the hybrid cycle OTEC, surface water of the ocean is flash evaporated into the vacuum chamber as in the open cycle OTEC (Cavanagh et al., 1993), and the low-pressure steam is being condensed in the ammonia evaporator. It must be mentioned that the low-pressure steam acts as heat carrier among ammonia and ocean water in the evaporator. Then, ammonia vapor passes through the turbine to generate electricity. This used ammonia vapor is being condensed on the surface of the condenser due to the deep cold water.

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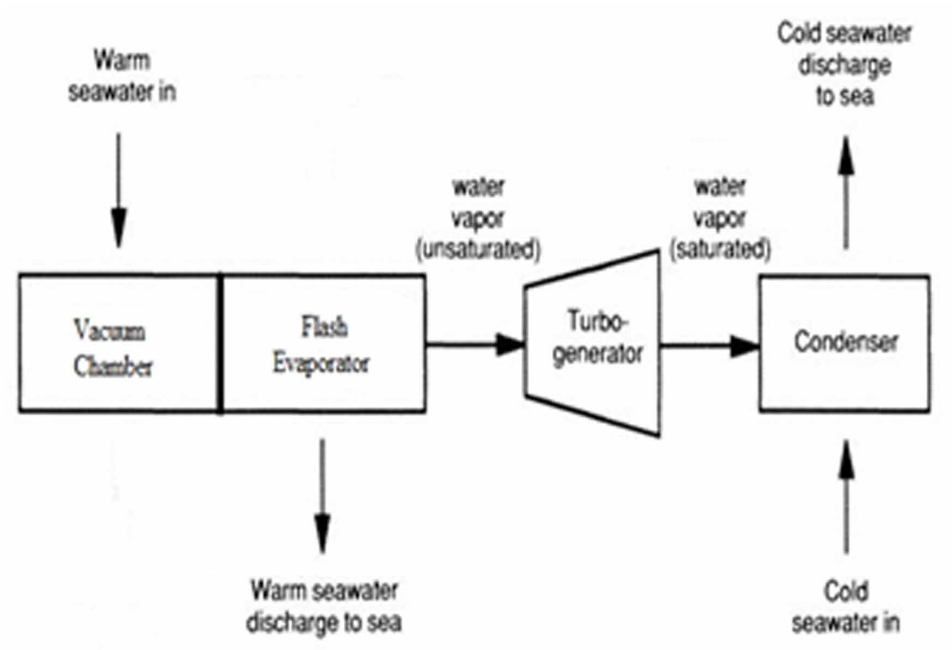
Figure 14. Open cycle OTEC process
Source: Uehara et al., 1990



All of the steam can't be condensed in a condenser. The rest of the steam is being condensed in the vent condenser. Ammonia from the condenser and the cold deep water of the ocean is used as coolant in the vent condenser. Hence, the hybrid cycle OTEC system is used for the simultaneous creation of electric power (Vega, 2002). The basic working diagram of hybrid OTEC is shown in fig. 15.

Advantages and Disadvantages of Ocean Thermal Energy

Advantages

a) Ocean thermal energy is clean and environment friendly renewable energy source.
b) Ocean thermal energy conversion power plants can produce simultaneously desalinated water (water without salts and minerals) and electric power.

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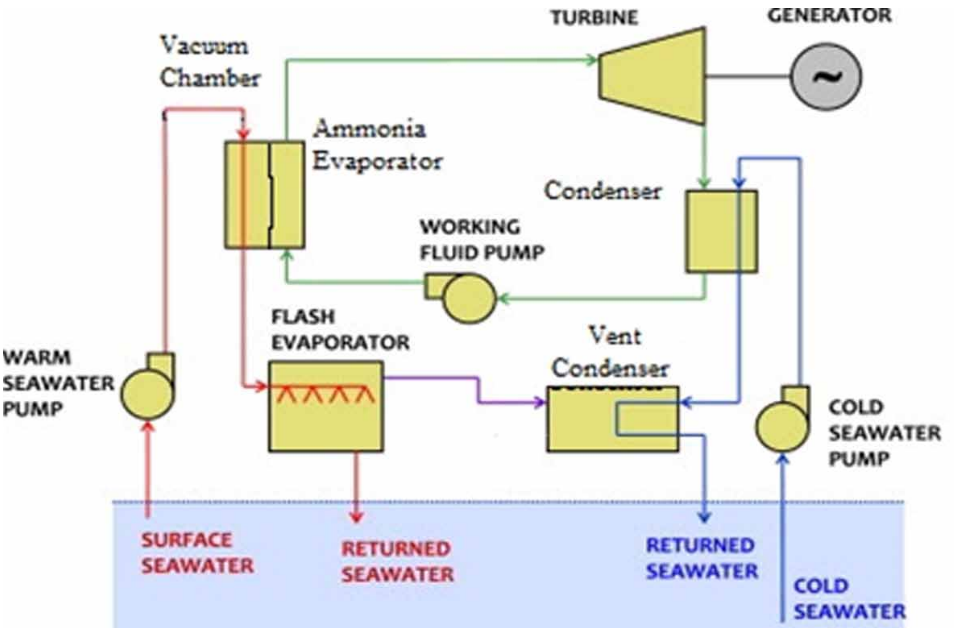
Figure 15. Hybrid cycle OTEC process
Source: Vega, 2002



c) OTEC plant contains cold water which can be used in other applications such as refrigeration and air conditioning.
d) OTEC plants can generate power continuously and the generated power is independent of weather.
e) There is very small variation in generating output power from ocean thermal energy.

Disadvantages

a) Construction cost of an OTEC plant is very high.
b) Efficiency of an OTEC plant is very low.
c) Closed cycle OTEC plant used expensive working fluids.
d) OTEC plant requires large size of turbines due to the low-pressure steam is used in the open cycle process.

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CONCLUSION

Ocean energy is clean renewable energy resource and it is capable to generate electricity continuously without polluting our environment. Ocean energy reducing the dependency of fossil fuels so that, there is no emission of carbon dioxide by using of an ocean energy. The predictability of tidal, wave and ocean thermal power is another advantage of an ocean renewable energy. So that, many of the countries target to harness ocean energy sources to fulfil the increasing rate of energy demand in the world.

This study provides a brief analysis and details of all the forms of the ocean energy and the current technologies used to generate electricity. There may be an exceptional potential to generate electricity in massive amount from various forms of the ocean energy. And the technological advancement in the field of the ocean renewable energy provides a significant amount of electricity in all over the world. According to the International Renewable Energy Agency (IRENA) report, total capacity of all the forms of the renewable energy in the world was recorded nearly 2532 GW in 2019. Capacity and the production of the ocean renewable energy in the world was recorded nearly 531 MW in 2019 and 1002 GWh in 2018 according to the IRENA 2020 report.

Ocean energy is more dependable and sustainable energy source in comparison with other sources due to the environmental impacts. However, the technological advancement in the field of the ocean energy should be more focused to achieve high potential.

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Chapter 7
Real-Time Monitoring of Smart Meters Based on Blockchain Technology

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ABSTRACT

In this chapter, the authors primarily discuss how blockchain is being utilized in smarter grids across the globe and how some use cases can be a good fit as a technology. They ensure the reliability and uninterrupted power supply to end users by using smart metering in micro and macro grids, which is possible with novel technology that is transparent and without any cyberattacks/hackers: blockchain technology (BCT). In this chapter, BCT is implemented significantly at micro/macro smart grid network. Such a network would give efficient improvement and be interesting.

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INTRODUCTION

In this chapter primarily discuss how blockchain is being utilized in smarter grids across the globe and how some use cases can be good fit as a technology. Currently from a blockchain point of view the energy market is somewhere around USD 180 million dollars and it is expected in next five years it will grow to something like 5000 USD. Different businesses are actually using blockchain for various things but then particularly for financial transactions and interactions because it offers a secure way of secure channel for doing business, managing data and all that now it has really made a significant impact on the operational cost in reducing the operational costs and maintaining the data integrity one can reduce the capital expenditure for that matter in terms of adoption (Gao, 2018). That's the reason why globally the energy markets are looking to blockchain as a long-term solution to most of the problems at the current. As we know, energy segment is facing a couple of key players which are doing some really fantastic work in terms of blockchains in energy segment particularly power ledger .A network of computers now as they are distributed network computers they do not provide any scope for hackers to try and play with the system for two reasons. One is the blockchain is basically a string of blocks connected to each other until acted to each other which are more like in cryptographically hashed right (Beck et al., 2016). So the hash of block 0 will be used to encrypt the block 1 and the hash of block 1 is used to encrypt block 2 and so on . So the point is the longer the chain grows it is absolutely impossible to manipulate or alter anything in the chain. Since this is distributed so there are multiple partners in the business network who will have a copy of the same ledger so importantly if any hacker tries to change or to manipulate a content in a particular segment of a ledger, it will automatically get invalidated and it will be of no use because there are so many nice good copies available on the network which can be used from there onwards and that's the reason it has hardly any scope for a hacker to do anything there and that's a reason why so many industries are working towards adoption of blockchain from the industry from the energy industry point of view blockchain is offering a new tempo proof mechanism for authentication, authorization and data exchanges (Cohn et al, 2017; Kumar, 2020; Mika & Alexander, 2020). These are the three basic tenets where one can see a lot of adoption in energy grids from blockchain technology point of view .

Relying on automation and remote access because of which there are a couple of security concerns which we need to deal with. Particularly two majors

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things, one is the authentication which is the verification that someone who is entering into the system is a genuine person having the right identity to do it and second is the authorization that the verification is someone who does enter has the authority to do what he has to do so. The point is authentication and authorization are two important aspects where smart bits needs to be tackled because of automation and remote access. If one can see a few application areas of blockchain in a smarter grid, first is prevents hacking in malicious attacks. Since blockchain has a security which is enabled through a public/private encryption with key access. So anybody who is trying to get into a system must verify the credentials, must verify their energy and their authentication to do anything on the network. Blockchain is the necessary technology to really make the power grid safe.

MONITORING OF SMART METERS

Smart meters are penetrated widely into the energy sector dominantly in the distribution systems and also which performs in the cyber security point of view (Albu et al., 2017). In general smart metering should have intelligent monitoring of consumption, bi-directional data transmission, increased security of supply, higher efficiency and distinct tariffs depend on overall consumption and grid load. Usually in smart metering solution both utility company and customer should be able monitor hourly, daily, weekly and monthly consumption. Also in this micro grid system, meters can be precisely arrival from the system for controlling the devices at discrete remote locations. The data from these meters is communicated to head end systems. From this head end system data goes to meet a data management system and subsequent to smart lab for the purpose of analysis The worth of smart metering solution is provides info in which being consumed and delivered on a quasi real-time basis (Renner, 2013).

VARIOUS APPLICATION

There is an application area where blockchain can be really put to a good to use. It can become the backbone of a secure and efficient infrastructure (Lombardi et al., 2018) .Now with the migration of the industrialization one can have seen a lot of migration of population towards urban areas in the last

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few decades and which actually resulted in acute shortage of basic amenities that a particular city could provide .The reason is the resources were not able to scale up the way the population poured in and the urbanization happen to establishing Smarter Cities. In the creation of infrastructure for smaller cities and all that now again how blockchain can help as talking about identifiable identities and authorization .

Authorized access one can use blockchain for recording and storing transaction in an immutable form which can make the data exchanges between these distributed gadgets in a very seamless and a cost-efficient way.It can actually provide a security that is very much needed for a smarter City to really work because as such the entire city is interconnected in terms of all those devices and services which the city offers (Pieroni et al., 2018). A blockchain can really help in creating a peer-to-peer energy trading involvement. This is something which is already being worked on with. So as the conventional sources of energies are depleting very rapidly, the governments across the globe are looking for alternative energy sources in terms of renewable energies. It may be solar or wind or whatsoever (Winter, 2018; Kamath, 2018).

IMPLEMENTATION OF BLOCKCHAIN UNDER DISTINCT AREAS

Now the problem is all the generations are small micro grids. It needs to be fed back into the grid so that people can buy. Actually the consumer of the electricity is now a producer as well, but the point is how to effectively use this energy which is getting generated .So for that matter a blockchain based system provides an efficient peer-to-peer trading mechanism for our localized housing complex which is generating some sort of energy. If one has a house-X which generates some excess solar power feeding it back to the grid. All information is recorded on a blockchain, how much energy is being generated how many it's been consumed at what point in time it's been generated and consumed and what is the relevant rate at that point. All on blockchain it allows for a seamless and legitimate way of doing. As we know peer-to-peer business trading, which is another good application of blockchain from energy grid point of view in terms of electricity certificates (Zhao et al., 2020).

Conventionally electricity certificates have been used big time in terms of trading and all. So in a grid the electricity is in the form of non-conventional

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sources like Sun wind or so many other renewable sources.To keep track of how this clean energy is produced and how it can be distinguished is important. There are governments around the world have actually created our system based on credible certificates. Author call them as energy certificates. This conventional approach of managing these certificates is really a big task. When a renewable power plant generates units of electricity today or metered spits out the data and it basically gets logged in a spreadsheet (Mannaro et al., 2017) .The suspect sheet is then sent to the registry which gets the data entered into a new system and the certificate is created (Cheng et al., 2018). Once a healthy weight is created, a second set of brokers basically deals between buyers and sellers of these certificates and some third party then verifies these certificates after their purchase (Li et al., 2020) . So overall it's actually such a buzzing tank system which racks up so much of transaction costs and there is definitely a scope of so much of accounting errors as well. In this particular entire process now what if the meter could directly write that particular data which it is generating on a blockchain base ledger. So the moment we do that it provides a very basic sort of a trust that the unit being created or generated. So if we can manage the electricity certificates over a blockchain base network they can be nothing better of handling things. Like that consider the owner of a small power generators like rooftop panels or some wind turbines or that they are not able to maximize their profits (Peck & David, 2017).

Because in the current system they are not able to make distinction between the renewable energy produced and the conventional energy produced on the grid. Electricity provider to get back the compensation for which customer generated the electricity in a blockchain based system which can be almost instantaneous in real time that makes the difference. Hence the system is decentralized in to small micro grid producers which can really make their businesses profitable. Suppose the producer is producing electricity and it is being stolen by some other person on the same Lane then it can be over come by employing block chain technology in micro grid. Since it's easy to manage on a blockchain based network this notion has been made possible and hence customer knows the entire concept of electricity certificates has been pretty much eased outweigh and simplified. The first blockchain distributed database for managing electricity grid is developed by IBM [Kamath, 2018; Bhuvana & Aithal, 2020). It basically used the permission from blockchain network which uses the hyper ledger fabric to integrate the capacity of the surplus electricity being supplied, the households of the electricity cards all a like that. So that the energy transition actually had a new source which was

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basically fed into the grid. That was one thing, the second is transmission system operator to use innovative blockchain technology for managing the entire electricity grid.

ECONOMICAL IMPACT BY BLOCKCHAIN

There are so many other ways of using blockchain in this particular scenario. Another way they're doing is they are using intelligent electricity meters for providing benefits to energy producers and end-users in terms of improved data collection. Now what will happen is since these meters are properly secured, the blockchain technology can make smart meters more secure and it can actually prevent security gaps by acting as a decentralization transaction lock and then it can also create necessary conditions for peer-to-peer trade where the locals actually trade energy in a more efficient manner (Zhang et. al., 2020). Now blockchain has really provided renewable energy macro gates which is an efficient way of enforcing real time differential billing as well. So with the blockchain based system this overall documentation becomes a lot more transparent, a lot more flexible in terms of people to adopt to it and it is hence far more better than a conventional system. Block chains are really good at managing micro grids and smart grids. A smart meter can directly log in the units it has generated on a blockchain ledger. On an energy trading again blockchain can be a very effective technology to use as there are smart contracts of the chain codes are autonomous codes. They are configured for a certain business process. Nobody can manipulate it (Yu et al., 2018; Lo at el., 2017). So one can be pretty ensured that whatever is being done is actually according to the rules and if customer know contract terms so there is a lot more trust in the system when there is a trading network based on a blockchain based technology .Similarly real-time pricing is again one aspect where energy trading can really benefit a lot. Peer-to-peer trading where buying and selling of electricity is being done by the neighbours within a same neighbourhood (Devine & Paul, 2019; Livingston at el., 2018). Another important area where blockchain can be used in smart grids is control and security. The approach of uses can be the compliance monitoring. Now in all industries there is a good set of checks and balances being put and all need to adhere to those compliances and governances since blockchain is naturally compliant. So the monitoring is made very easy because it is embedded in the system. It's not that to have additional measures to do the compliance which

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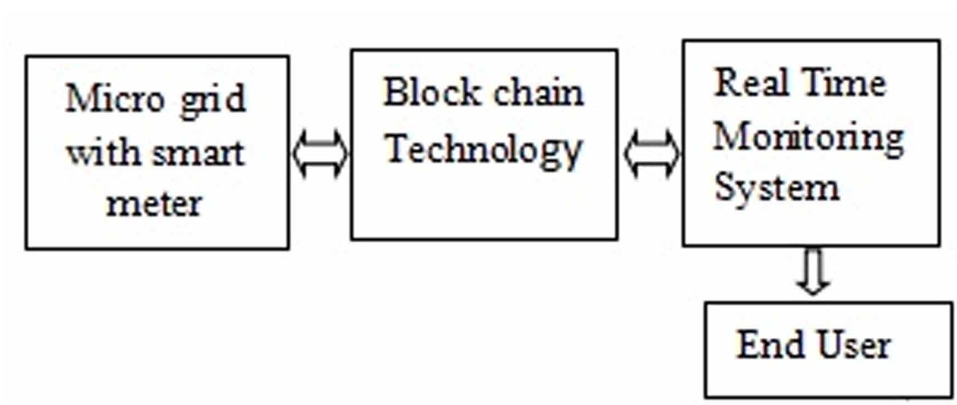
is really a great saving from our manufacturers. From our producers point of view another good blockchain use case in terms of payment schemes. One can have some electricity tokens which customer can use as barter maybe to buy and sell using those tokens and even those tokens can be monetized with the banks as there is a fiat currency (Chen, 2018; Oliveira al el., 2018). The customer can have wallets in which one can actually store those tokens that's another way of utilizing and making payments over a blockchain based system. Blockchain can really ease out the cross-border payments. The payments are made simplified and easy and effective in more real time compared to so many days which used to take. Using a blockchain base technology another very important aspect is supply chain and logistics in terms of inventory management. Now if you remember the example of the food security where we know how supply chain is basically integrated into the overall retail system (Tse at el., 2017; Hilt at el., 2018) .We will find that it has really made a lot of difference in terms of realizing the value reducing the cost giving a more visibility making it more transparent in that way. So there can be so many use cases where a blockchain can be really put to good use in a smart grid and of course there's another use case towards decarbonization where we can use blockchain to regard all those to have footprints which are being generated. A block diagram representation of blockchain and its real time implementation for reliable electrical energy supply to end user is shown in figure.1.

Figure 1. Implementation of block chain in real time system



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MAIN FOCUS OF THE CHAPTER

This chapter mainly focuses on the real time monitoring of smart meters using blockchain technology which is effectively utilized for reliable and efficient usage of electrical energy by end users

FUTURE RESEARCH DIRECTIONS

It can be effectively employed in case of electrical distribution system which is a more challenging application in real time system. Also it can be utilize in inter disciplinary areas like medicine, erypto currency etc.

CONCLUSION

In order to maintain sustainability supply to consumers novel technology always welcome the world. This article which give importance of smart meter effectively used in the smart grids by considering the proposed blockchain technology. The proposed technique which given equal importance to contractors, consumers, traders and government bodies.

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Chapter 8
Matrix Converter:
A Solution for Electric Drives and Control Applications

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ABSTRACT

The matrix converter (MC) has recently attracted significant attention among researchers because of its applications in wind energy conversion, military power supplies, induction motor drives, etc. Recently, different MC topologies have been proposed and developed which have their own advantages and disadvantages. Matrix converter can be classified as a direct and indirect structure. This chapter aims to give a general description of the basic features of a three phase to three phase matrix converters in terms of performance and of technological issues. Matrix converter is a direct AC-AC converter topology that is able to directly convert energy from an AC source to an AC load without the need of a bulky and limited lifetime energy storage element. AC-AC topologies receive extensive research attention for being an alternative to replace traditional AC-DC-AC converters in the variable voltage and variable frequency AC drive applications.

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INTRODUCTION

Electrical energy is widely used in a wide range of modern industrial and home applications, from low to high power. The AC mains electricity, on the other hand, cannot be used directly in many applications. In variable speed drives, for example, a variable frequency and amplitude AC power source is required to run AC motors at varying speeds. In addition, conversion of AC/DC power is required to run DC motors at varied speeds. So, power converters are required in many industrial applications. Previously, DC motors were frequently preferred because their torque could be easily adjusted. (Klumpner et al., 2000) The DC motors have replaced by AC motors nowadays due to the maintenance issues of DC motors have because of brushes & commutators. As a result, AC motor drives have gotten a lot of press. Many unique gadgets that sustain the AC/AC power conversion process have been devised and created in order to properly regulate AC motors. (Wheeler et al., 2008)

THREE PHASE AC/AC POWER CONVERTER

AC/AC converters are commonly employed for power transmission from a 3-phase source to 3-phase load, such as changeable speed drives & configurable frequency, phase and amplitude. To increase the performance, efficiency, and dependability of the systems in which they are used, different type of power converters are employed these days. (Gupta et al., 2010) A taxonomy of converter families utilised in electrical drive applications is shown in Fig.1.1. The two type of power converters are, indirect converters, that involves DC-link elements linking the two AC systems, & other are direct converters, that offer direct AC/AC power conversion. (Chlebis et al., 2010)

2-level diode-rectified voltage source inverters (VSI) generally used in all indirect power converter circuits that convert DC input voltage into AC output voltages. The extensively utilised inverter topologies for 3-phase applications are the 3-phase 2-level VSI depicted in Fig.1.2. (Satish, 2007)

In 3-phase arrangements, the cyclo-converter is the most often used topology, which employs semiconductor switches for linking through the power source to the load, exchanging 3-phase AC voltage into 3-phase AC voltage by variable magnitude, frequency and permits flow of power in both directions. This direct converter's operational output frequency must be lower in comparison to input frequency. Matrix converters, also cyclo-converters,

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have seen increased attention as direct converters in past time. (Chlebis et al., 2010; Gupta et al., 2010; Satish, 2007)

Figure 1. Categorization of converters (low-to-high power drives)

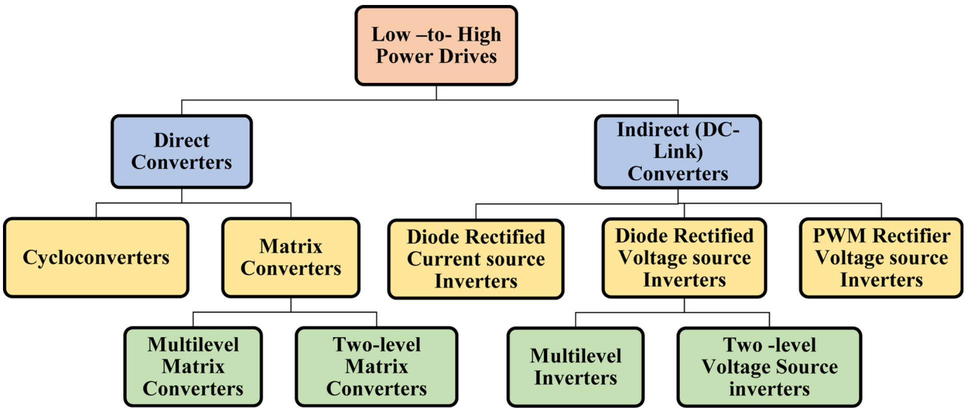
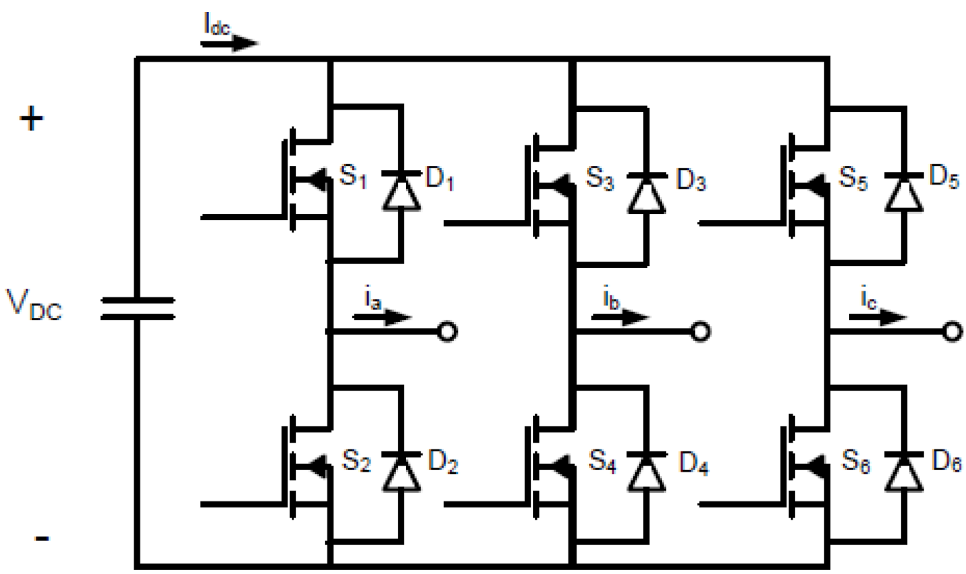


Figure 2. 3-phase 2-level VSI circuit technique



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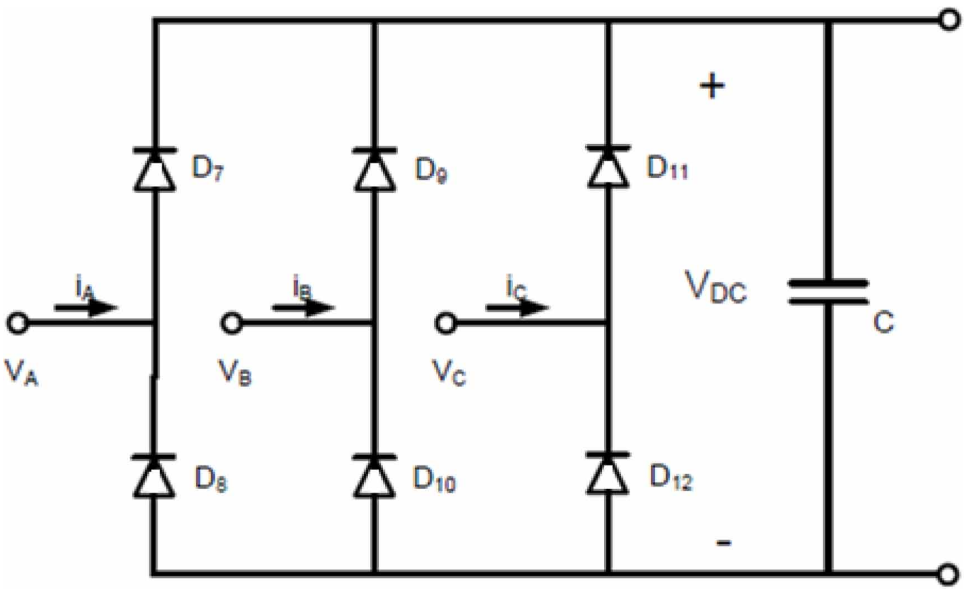
Indirect (DC-Link) 2-Level Voltage Source Converters

As previously stated the DC/AC converter is a 2-level voltage source inverter. DC voltage, on the other hand, is not a common voltage. Rectifier structures are often employed to create DC voltage. A rectifier is a device that transforms AC into DC. The three-phase diode rectifier, as shown in Fig.1.3, is the most common rectifier structure. A DC-link capacitor is also included in the circuit to ensure that the DC-link voltage is ripple-free.

Figure 3. Diode rectifier stage



Even when fed with a balanced sinusoidal voltage, generally converters employ diode-rectifiers (followed by a DC-link capacitor), that draw non-sinusoidal currents (ia, ib, ic) voltage (Va, Vb, Vc). The VSI based on diode rectifier- may be a good resolution during consideration of load side currents (ia, ib, ic), but its supply side currents (ia, ib, ic) are extremely distorted, carrying high amounts of low order harmonics, which may further interfere with other electric systems in the network. Furthermore, current flow through diodes cannot be reversed. As a result, bi-directional power flow requires the use of an auxiliary circuit. (Alesina & Venturini, 1989; Ziogas et al., 1986) Another disadvantage of this topology is this. The VSI structure based on a diode rectifier is shown in Fig.1.4.

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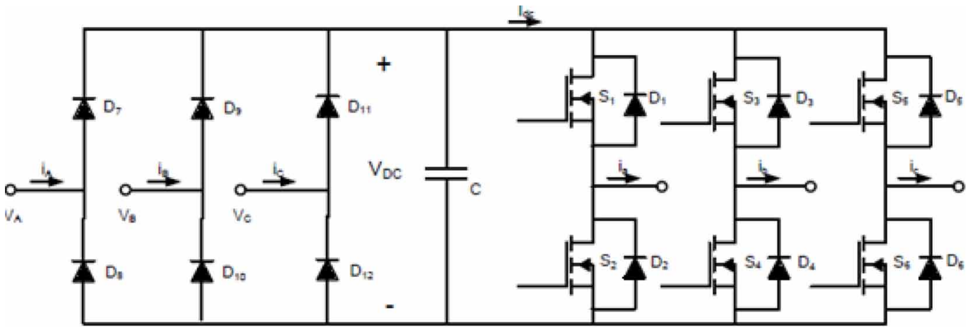
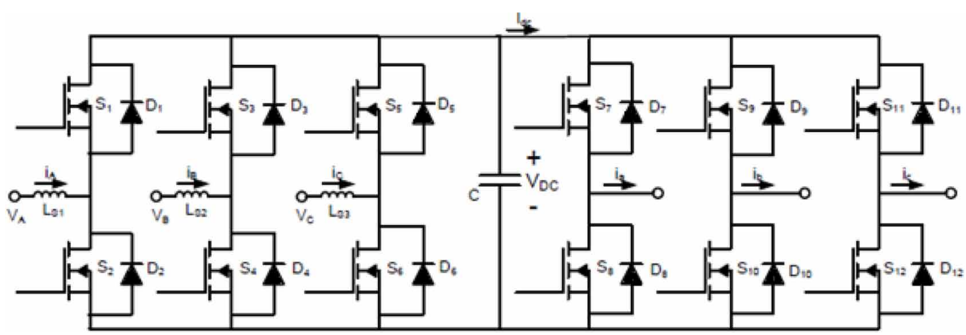
Figure 4. Diode rectifiers based VSI



As shown in Fig.1.5, the controlled bridge rectifier, rather than a diode rectifier, is a common clarification for harmonics in input current waveforms and 2-directional power flow difficulties. From the AC supply, the Back-to-back voltage source converter (BBVSC) extracts sinusoidal current waveforms (ia, ib, ic). A DC-link capacitor is present among the controlled bridge rectifier; Inverter Bridge and supply filter inductors. In low and medium power conversion, the supply filter inductor (Ls) present at the input terminals of the controlled bridge rectifier is too larger than the DC-link capacitor. As a result, this traditional indirect converter has a large volume.

Figure 5. Back-to-back voltage source converters



MATRIX CONVERTERS

Concept of direct frequency conversion was first proposed in 1920. Generally, The Direct AC/AC converters may be divided into two types. Usually, the

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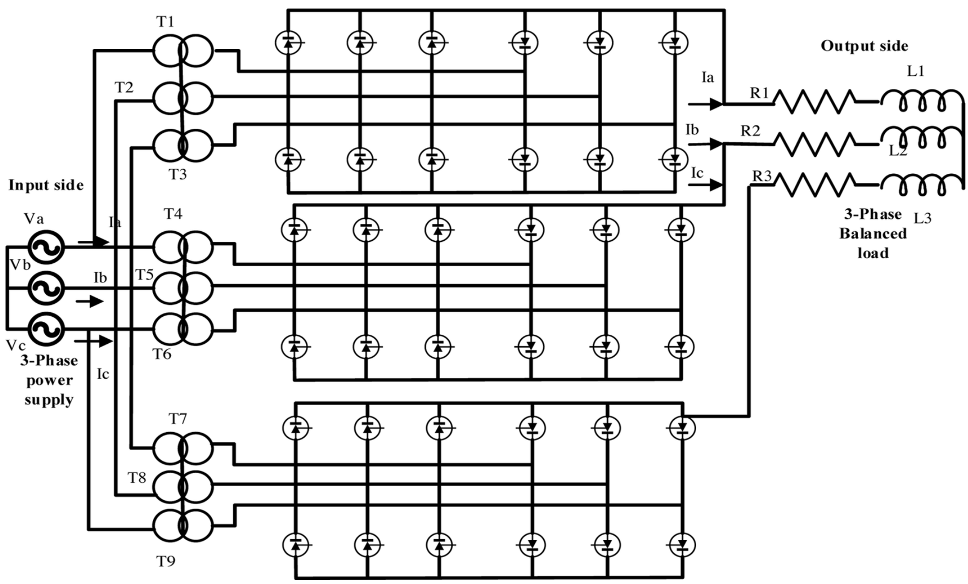
initial category of converters can be employed if the functioning output frequencies are lesser in comparison to supply frequency. The cyclo-converter was the name given to this converter that converts AC voltage waveforms, such as those from the main supply, to lower frequency AC voltage waveforms. The first semiconductor-based cyclo-converters were created in the 1960s, following the introduction of the thyristor (Ziogas et al., 1986). Figure 1.6 shows a typical phase-controlled thyristor-based three-phase to three-phase cyclo-converter. They're frequently used in 3-phase applications.

Figure 6. 3-phase to 3-phase phase-controlled cyclo-converter



The amplitude and frequency of the input voltage supplied to a cyclo-converter is fixed in most of the power systems, while the amplitude and frequency of the cyclo-output converter's waveforms are usually variable. The cyclo-load converter's voltage and input current waveforms are significantly distorted, and the input power factor is low. More switching devices, on the other hand, can improve the quality of the output waveforms. Furthermore, the output frequency is commonly set to half that of the input supply. Because normal loads cannot survive the voltage distortion caused by higher input to output frequency ratios, larger input to output frequency ratios must be avoided. Thus, the thyristor's resilience and minimal losses are the only advantages left. Because of the restricted output frequencies and poor harmonic

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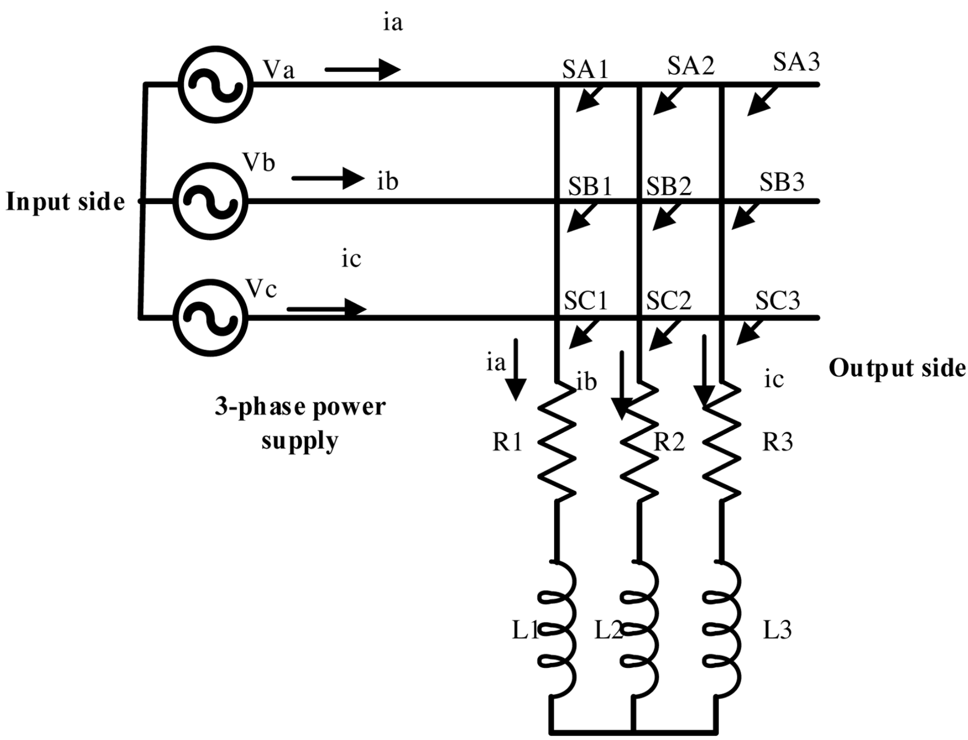
performance, the cyclo-converter cannot be considered an optimal choice for low and medium power level converters. However, because of its low losses and resilience, the cyclo-converter might be considered the best choice for high-power levels. (Wheeler et al., 2002)

The matrix converter is the second type of direct converter (MC). It is extremely adaptable, having no restrictions on the operational output frequencies. With no intermediate DC conversion or DC energy storage parts, a matrix converter converts direct AC/AC power from AC utility to AC load. As a result, numerous conversion steps are replaced with a single power conversion stage.

In comparison to indirect AC/AC power converters with DC-link components, the converter size and volume can be substantially reduced. As a result, direct converter topologies may offer a solution for applications that prohibit the use of large passive components. In Fig.1.7 the MC's fundamental circuit is depicted.

Figure 7. Simple circuit of direct matrix converter



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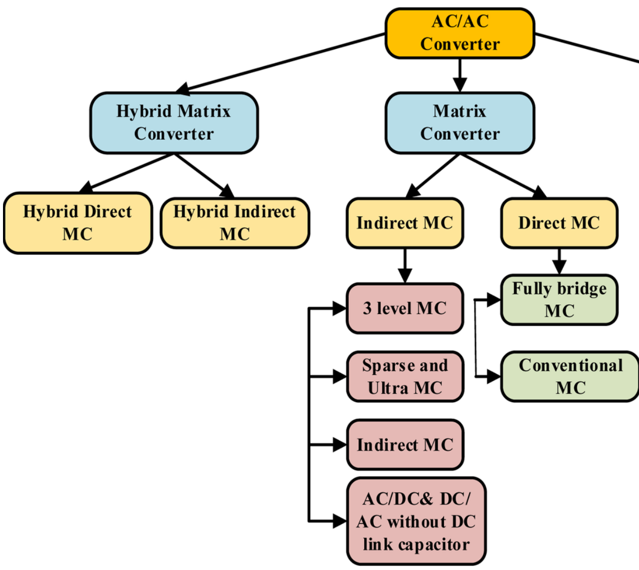
As shown in Fig. 1.8, there are a variety of AC/AC converter options. The most common method is the standard DC link converter, that have 2 converter stages connected in the DC link by an energy storage device (inductor or capacitor), as illustrated in Fig. 1.9 (a) (b). The instantaneous decoupling of the two converter stages is assist by energy storage element supports, also allows the input side PWM rectifier and the output side PWM inverter to be operated separately.

Figure 8. Categorisation of 3-phase AC-AC converter



The Matrix Converter is another type of AC/AC converter, consisting of an arrangement of 4 quadrant 2-directional switches that connect the output terminals to the input grid phases without the use of an intermediate storage element. (Glinka & Marquardt, 2005)

There are several more topological versions of the Matrix Converter (MC), such as the Sparse MC and Hybrid MC concepts. As demonstrated in Figure 11 conventional Direct MC performs conversion of power in a single step. On the other hand, an indirect MC (Fig 1.10 (b) exists, which, like back-to-back converters, has distinct stages for voltage and current conversion, but no storage element in the DC connection.

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Figure 9. Voltage dc-link converter

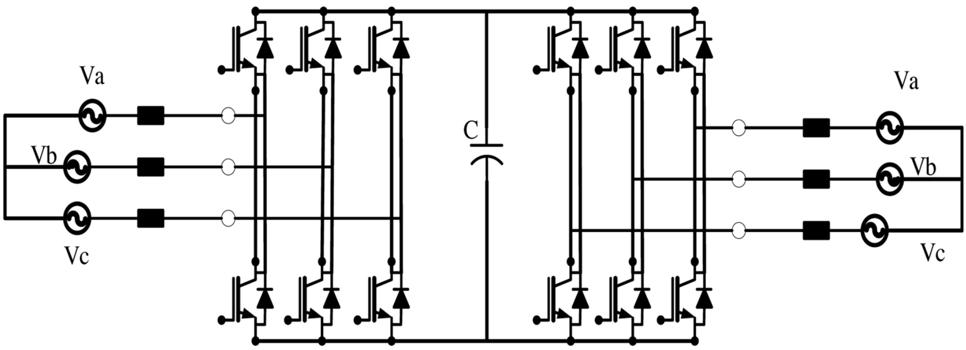

Figure 10. Current dc-link converter

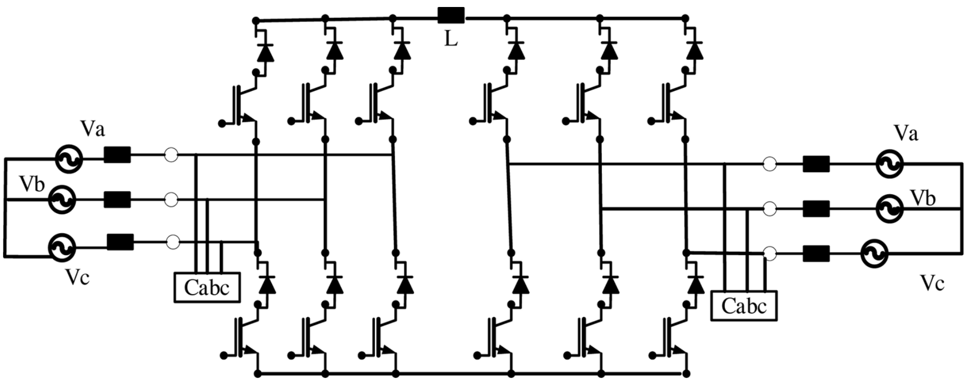

Figure 12. Indirect matrix converter

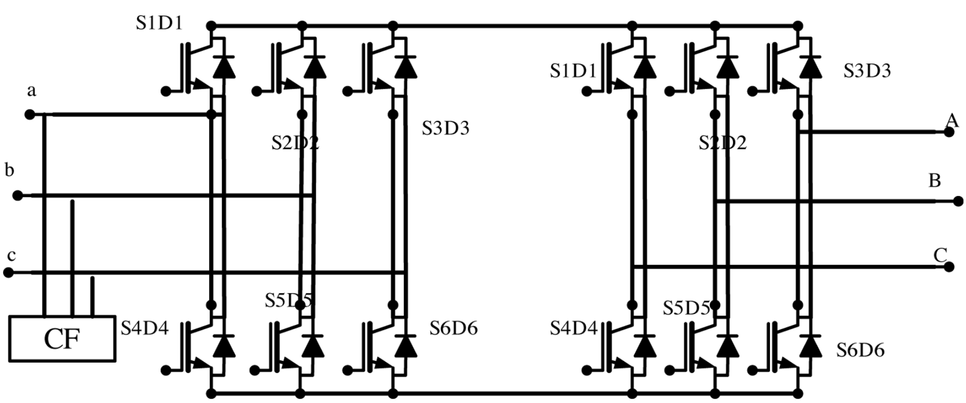

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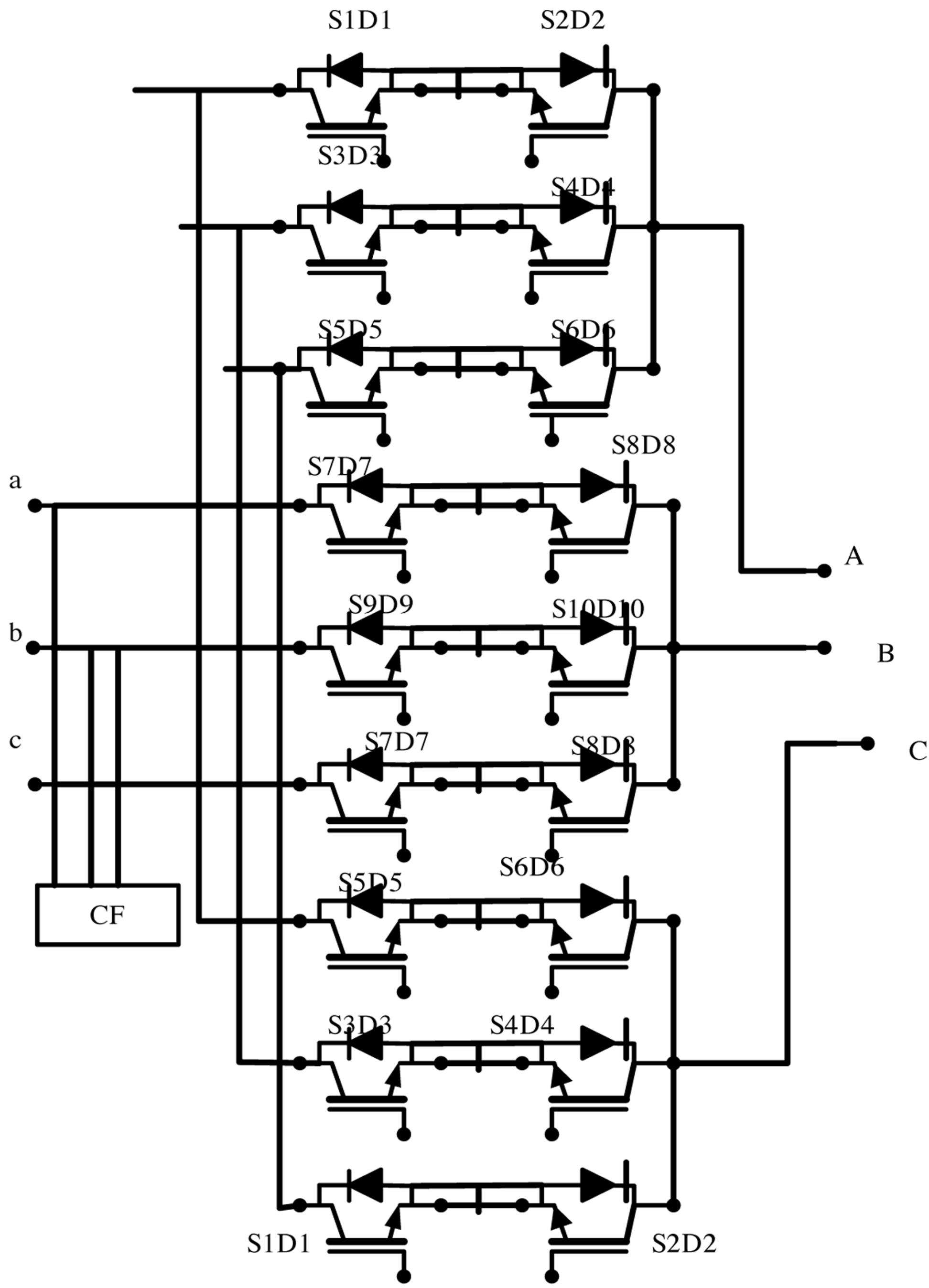
Figure 11. Direct matrix converter



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The MC architecture has promise for general power conversion like AC-DC, DC-AC, DC-DC, and AC-AC converters because of autonomy of voltage form and frequency on the input and output sides. The work of (Venturini, 1980), who offered a mathematical analysis and introduced the Low-Frequency Matrix Converter, is where the true evolution of the matrix converter begins. The Modulation Matrix idea is used to characterise the matrix converter's low frequency behaviour. The output voltages are obtained by multiplying the modulation or transfer matrices with the input voltages in this method. In the linear modulation range, the maximum output voltage accessible to the matrix converter is limited to 86.6 percent of the input voltage.

MODULATION TECHNIQUES

The Conventional MC, as shown in Figures 11 and 12, is a configuration of 9 bidirectional switches that are organised in such a way that any output supply may be linked to any input supply at anytime. Because of the needed input & output voltages, the switching duty cycles are adjusted to provide the desirable output waveform.

Different modulation techniques presented in literature, on the whole, produce switched voltage or current pulse guides with the similar elementary amp-second/volt-second or usual as the reference waveform.

The common problem along such switched waveforms is that they contain undesirable harmonic components that diminish energy superiority. As a result, the best modulation approach is one that minimises input current and output voltage harmonic deformation, as well as power losses in device. Carrier-based methods and space vector methods are two types of modulation strategies for MCs.

As illustrated in Figure 13, there are various algorithms that fall into these categories. (Bradaschia et al., 2009; Venturini, 1980) proposed the first modulation approach rooted in mathematical calculation; however it only attained 50% voltage. Following which, numerous carrier-based and space vector-based MC modulation algorithms were created. For practical implementation, the carrier-based systems required moreover 3rd harmonic insertion or a changeable amplitude carrier, whilst the space vector-related techniques used search for tables and sophisticated estimate algorithms. Within the linear modulation range, a comparison of carrier-based approaches has been offered in the form of a modulation index. (Iyer Narayanaswamy, 2010; Luo & Pan, 2006; Meng et al., 2010)

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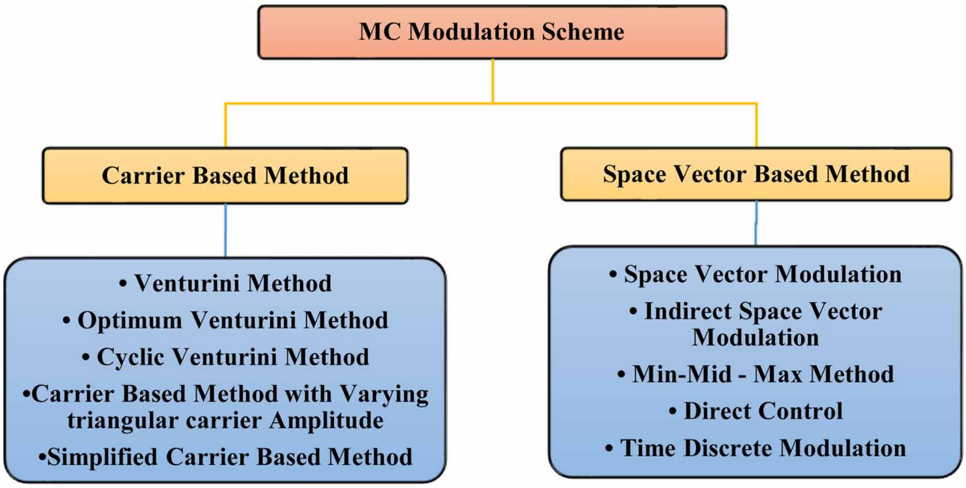
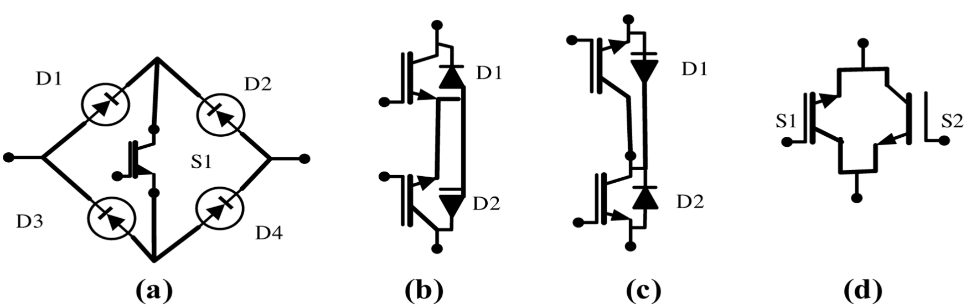
Figure 13. Matrix converter modulation methods



Device Realization and Commutation

The realisation of a bidirectional switch is the first issue with MC. A bidirectional switch is one that can conduct current in both directions while simultaneously blocking voltage from either polarity. However, because a true bidirectional switch is not available, unidirectional apparatus are properly integrated to make a switch with bidirectional ability. Figure 1.12 depicts several bidirectional switch setups.

Figure 14. Various configurations of 2-directional switches (a) Diode Bridge Switch cell (b)



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Common Emitter IGBT (c) Common Collector IGBT (d) Reverse Blocking IGBT

The commutation difficulty is another issue that has prevented the MC for extensively adopted in industrial uses. The MC is a combination of switches that expose the load's lack of a passive freewheeling path. To ensure safe commutation, any input voltage short circuits or load current breaks should be avoided. This means that the timing and synchronisation of the switch command signals must be developed with extreme caution. The 2-stage commutation and the 4-stage commutation procedures are proposed. Such techniques, however, rely on precision of calculated input voltage or output current, which can guide to commutation errors, as a result, switch breakdowns. (Muller et al., 2005)

Issues in Input Filter

Despite the fact that the MC is marketed like an "all silicon solution" due to nonappearance of bulky DC Link capacitors in comparison to standard VSI, moreover the input filter needs a least amount of reactive parts. From the input supply part, the MC functions as a current source converter, necessitating the use of an LC filter to reduce harmonics that cause voltage alterations. The problem with design of input filter is that it must be optimised because of reactive component necessity in an MC, that limits input filters to modest sizes.In other words, an MC's major benefit over typical DC Link converters will be lost if it uses massive reactive components. Various designs based on varying weights, switching frequencies, and modulation algorithms have been proposed. The following are the prerequisites for the input filter design:

1. To have a lower cut-off frequency than the switching frequency of the converter.
2. Capacitors and inductors must have the smallest possible weight, volume, and cost.
3. To minimise a deterioration in the voltage transfer ratio, minimal voltage drops owing to filter inductance at rated current are required.

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In addition, for an optimum filter design, some assumptions for system constancy, competence, and filter parameter deviation must be prepared. As a result, with such an optimised design is not simple effort, and it remains an outstanding challenge due to such modern harmonics and EMI diminution regulations.

Protection Issue

The MC, like any other power electronic converter, must be safeguarded from over- currents and over- voltages that could harm semiconductor components. Such over-voltages could be caused by a voltage spike from the AC mains or by switch commutation problems, resulting in output current interruption. Over-currents can occur as a result of short circuits on input or output side. Current freewheeling pathways for load de-energization must be provided to avoid the occurrence of such harmful over currents & over-voltages at the MC switches. (Andreu et al., 2008)

The clamp circuit is the MC's common protection method, which applies to all 9 bidirectional switches. As shown in Fig. 1.13, the clamp circuit has a capacitor coupled to every output & input supply via 2 speedy recovery diode bridges. Despite the fact that such clamp circuit safety techniques have the advantage of extremely easy and secure for every working circumstances, it does, however, have a number of disadvantages. To begin with, it expands some semiconductor tools in the circuit. On the other hand, clamp capacitor boosts the many reactive components in the system. Finally, the machine equivalent circuit parameters must be determined in order to construct a clamp circuit optimally.Another proposed protection strategy involves using varistors at both the output and input to disperse energy of several inductive currents generated by these varistors during incorrect conditions. (Pfeifer & Schroder, 2009; Wheeler et al., 2004)

Ride-Through Capabilities

To make an MC feasible for commercial use, it must have at least limited ride-through capabilities to avoid frequent system excursions and, as a result, shutdown. The approach used for traditional DC link systems is fairly close to the common solution.The approach entails disconnecting the machine from the grid and recovering power through load inertia in order to maintain a constant DC capacitor voltage in the clamp circuit. These capacitors might

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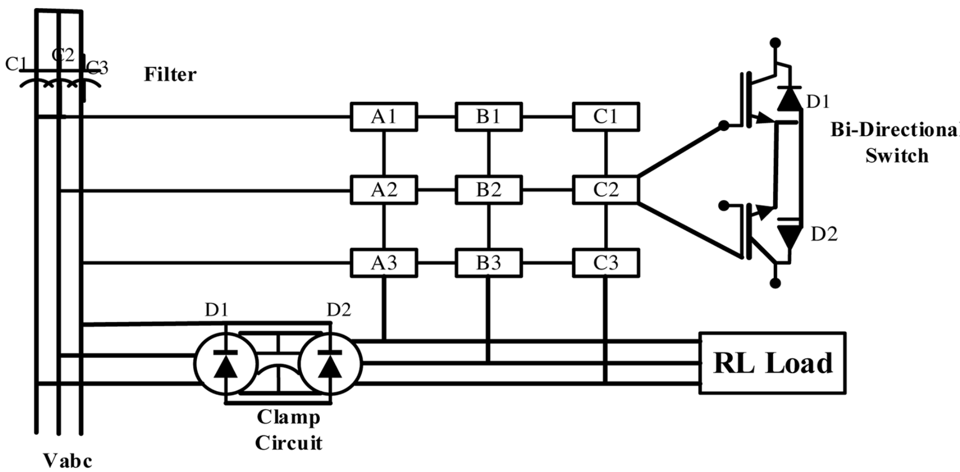
be attached with control circuitry, allowing the controls to be active for a partial time period. The controller resets the drive to its usual working position when the power system recovers. Another technique for MC fed ASDs to ride through voltage sags is to enforce stable volts/hertz operation and, if necessary, cut speed reference. (Klumpner et al., 2001)

Figure 15. Schematic of direct matrix converter



MATRIX CONVERTER TECHNOLOGY

The MC is a set of controlled semiconductor switches which links an m-phase supply with an n-phase load directly. The Matrix Converter (MC) developed through forced commutated cyclo-converters and is widely studied in recent years for more than three decades.

This chapter includes looks into Z source matrix converter topologies, as well as direct matrix converter topologies, indirect matrix converter topologies, and matrix converter topologies with fewer switches. Z-source matrix converters overcome the disadvantages of ordinary matrix converters with either buck or boost capability. Matrix Converter (MC) and its extended topologies have been the subject of research for the past three decades, owing to its appealing and desirable characteristics. The initial overview of MC technology, published in 2002, focused on single-stage MCs and was devoted to modulation, control, and strategies for solving the MC commutation problem (Arias et al., 2007).

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The following are some of the most desirable aspects of power electronics converters:

1. A simple and compact power circuit;
2. The generation of arbitrary amplitude and frequency load voltages;
3. Input and output currents that are sinusoidal;
4. For every load, operation with a power factor of one;
5. The ability to regenerate

Matrix converters can achieve these ideal features, which is why the topology has sparked so much attention. Through variable input power factor & sinusoidal input/output waveforms, it's a fascinating converter circuit. It is able of doing direct conversion of AC-AC power with the least amount of passive energy storage components. Theoretical analysis, control techniques, & performance concerns relating to the MC have all progressed significantly in previous studies (Pfeifer & Schroder, 2009). As reverse blocking insulated gate bipolar transistors (RB-IGBTs) can be best option to conventional back-to-back converters (Ge et al., 2012).

The configuration of a 3-phase voltage source matrix converter is shown in Fig.1.14 (Zhang et al., 2006). (VS-MC). The VS-MC can produce a desired AC output voltage while managing the input current waveform and power factor by manipulating 9 AC switches along suitable modulation technique (Klumpner et al., 2000). The VS-MC must be linked to an inductive load and is powered by an AC voltage source. The VS-working MC's concept is quite same as VS inverter.

A 3-phase input voltage can be selectively linked to every output terminal to create an active voltage to the load. All of the load terminals must be linked to one of the input source terminals to achieve zero voltage. On the input source side, no shoot-through switching states are permitted, and no open circuits are permitted on the output side. The VS-MC inverter, like the VS inverter, has intrinsic buck operation with an utmost voltage ratio of 0.867.

In Fig. 1.15 (Peng et al., 2005), the current-source matrix converter (CS-MC) can be regarded as the VS-dual MC's circuit. The current source for the CS-MC is a current source, and the load must be capacitive. There can't be an open-circuit on the input side and a short-circuit on the output side of the CS-MC. The output voltage of this device is always higher than the input voltage. The VS-MC and CS-MC can be used together to create a buck-boost matrix converter. Buck-boost matrix converters, on the other hand, require two stages and 18 AC switches, resulting in a high cost, a complex

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control method, low efficiency, and low reliability. In addition, to avoid an open-circuit or short-circuit in both converters, an appropriate commutation method must be used for safe switching.

Figure 16. 3-Phase voltage source matrix converter

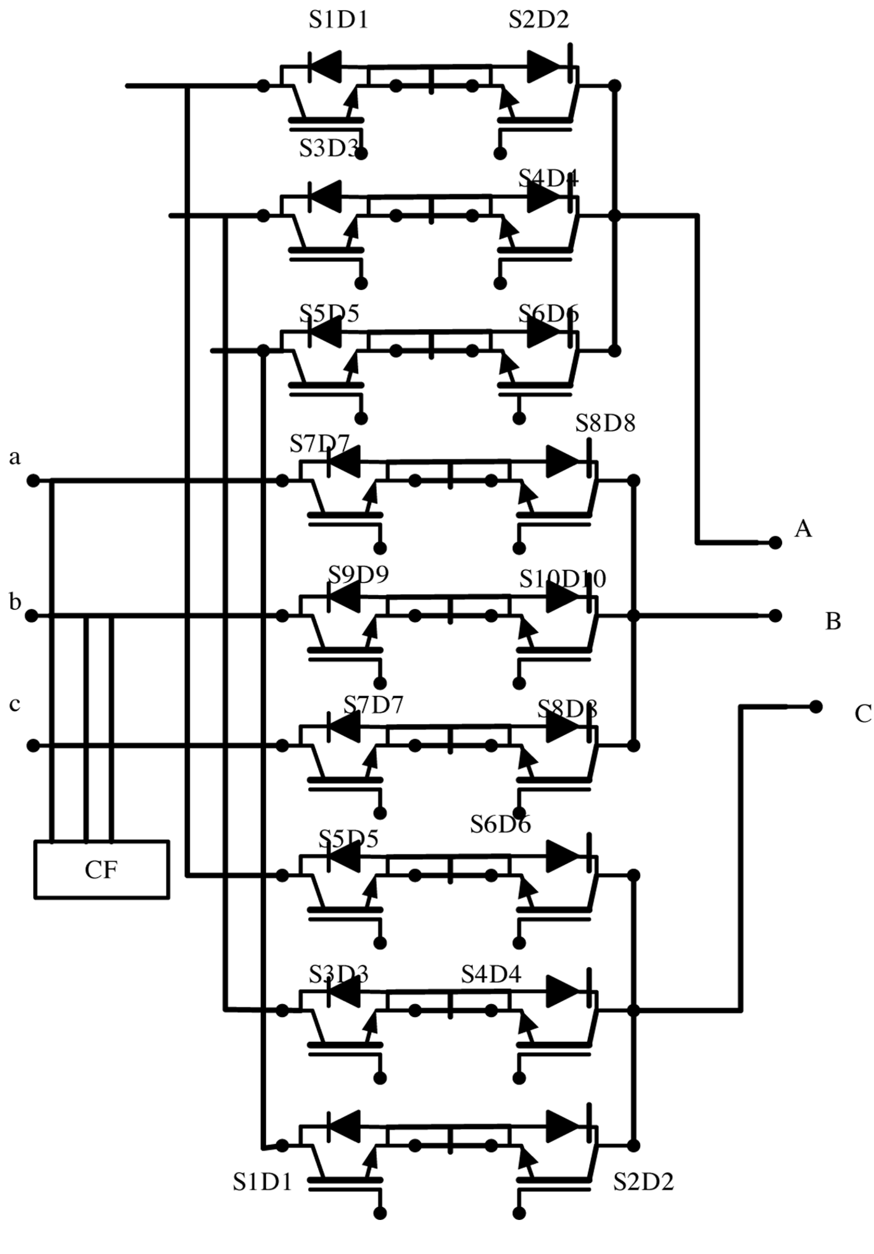

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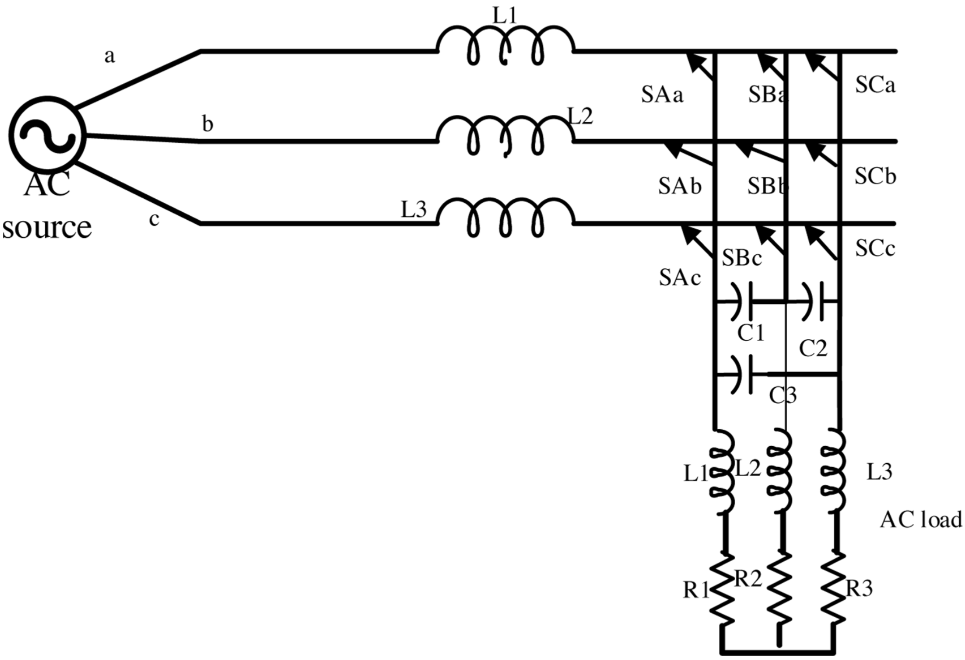
Figure 17. 3-phase current source matrix converter



Many authors have extended this concept to additional topologies with the recent creation of Z-source inverters by means of intrinsic real-time buck-boost capabilities (Peng, 2003). Their Z-source AC/AC converters, on the other hand, do not change the frequency (Anderson & Peng, 2008). This chapter examines a family of Z-source matrix converters (ZS-MCs) as well as various older matrix converter topologies.

Z Source Matrix Converter Topologies

The voltage source matrix converter and the current source matrix converter both have the issues listed below.

1. They can only be a buck or a boost converter, not a buck–boost converter. That is, the output voltage range they can achieve is either more or lower than the input voltage.
2. Their primary circuits cannot be swapped out. In other words, neither the voltage source converter main circuit nor the current source converter main circuit may be used for the source converter.

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3. In terms of reliability, they are susceptible to EMI noise.
4. An impedance-source power converter (Z-source converter) and its management mechanism for performing DC-AC, AC-DC, AC-AC, and DC-DC power conversion to overcome the foregoing difficulties of classic voltage source and current source converters. (Peng, 2008)

The ZS-MCs are depicted in Figures 18 and 19 which are made up of 3 parts: source-side MC, Z-source network, and load-side MC. The ZS-MCs, like the Z-source inverters, can be voltage-fed or current-fed. (Nguyen & Jung, 2010; Qian et al., 2010) The ZS-MCs' key feature is that they can do both buck and boost operations. They can, in other words, step up and down the source voltage.They're ideal for situations that require a lot of voltage boost. (Casadei et al., 2007; Casadei et al., 2005) Table (1) shows various methodologies and a comparison of matrix converter topologies (2).

Figure 18. Voltage-fed Z source matrix converter

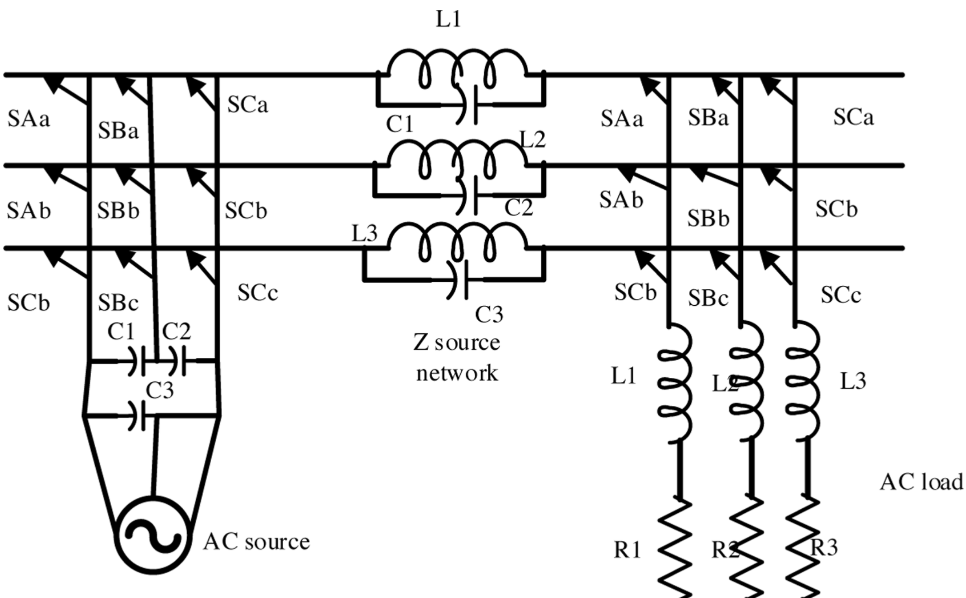

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Figure 19. Current-fed Z source matrix converter

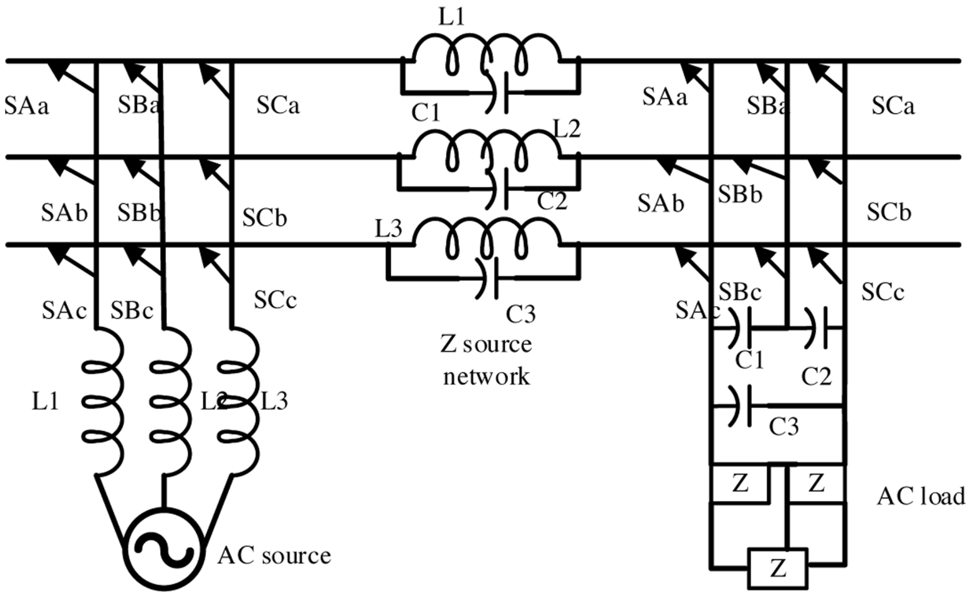

Table 1. Performance comparison of some MC control techniques

	Venturina control	Space vector modulation	Sliding mode control	Direct torque control	Predictive control	Hysteresis control
Complexity	Low	High	High	Medium	Low	Very low
Sampling Frequency	Very low	Low	Low	Very high	High	High
Switching Frequency	Very low	Low	Low	High	High	High
Dynamic response	Good	Good	Fast	Fast	Very fast	Very fast
Application range	Narrow	Wide	Medium	Narrow	Very wide	Medium

Table 2. Matrix converter topology comparison

Converter	No. of Active Devices	No. of Diodes	Isolated Driver Potentials	Simultaneous Buck Boost Capability
MC	18	18	6(CC), 9(CE)	No
IMC	18	18	8	No
SMC	15	18	7	No
VSMC	12	30	10	No
USMC	9	18	7	No
ZSMC	21	21	6(CC), 9(CE)	Yes

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Benefits of MC Over Traditional Back-To-Back PWM VSI

MCs provide a number of advantages over standard DC voltage link power frequency converters, including the following:

1. The all-silicon power module in MC's improves long-term stability of converter and existence when compared to the back-to-back converters' lifetime-limited big electrolytic capacitors.
2. With advances in semi-conductor power modules and power/weight ratios, and low power/volume, MCs have the potential to lower maintenance costs, making them more suited for applications where space is limited.
3. MCs produce sinusoidal output and input waveforms through the lowest possible upper order harmonics, as compared to today's commercial inverters.
4. They have built-in 2-directional power flow and a configurable input power factor.
5. The matrix converter employs single stage AC-AC shortest conversion to achieve a small loss system with at least 1/3 less loss than a traditional system.

Limitations of MC

Along with its benefits, MC has a number of drawbacks, which are described below:

1. In the linear modulation range, the maximum input-output voltage transfer ratio of MCs is limited to 87 percent.
2. It features complex modulation techniques for control and needs extra semiconductor switches because of the lack of subsisting bidirectional switches.
3. MCs are highly susceptible to voltage fluctuations and lack ride-through capabilities due to the lack of intermediate storage elements.

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MC Applications

1. The MC converter topology is appealing for applications that require the exclusion of electrolytic capacitors, the ability to produce decreased size and weight, greater density of power, unity power factor function and sinusoidal output and input currents. It encompasses industrial uses capable of megawatt levels, transportation uses and applications of renewable energy, among others. DTC and Field-oriented control motor drives are among the MC uses, as are wind power production techniques in doubly-fed induction topologies and squirrel cage induction machine (SCIG). (Mohan et al., 2003)
2. The MC is also being researched for application in diesel locomotive secondary drive systems. It's used to power cooling fan motors, traction motors, boost compressors, and air conditioners, among other things. A growing number of publications have recently been published that look into the possible usage of MCs in electric aircraft and hybrid car applications. (Yang et al., 2005)
3. The major roadblock due to development of an industrial MC Drive has been limited, and the primary steps toward industrialization have previously been made. (Friedli, 2012) However, MC still needs to develop in a number of areas before it can compete with or outperform todays widely used VSIs.

CONCLUSION

The matrix converter was introduced in this chapter as a future converter for AC drive applications, with the following advantages over conventional AC drive circuits.

1. Power harmonic suppression: Without any special precautions, achieves below 7% THD of input current and over 98% input power factor.
2. Longer working life: Because the main circuit lacks robust materials such as an electrolytic capacitor, it has a longer operating life and requires less maintenance.
3. De-rating is no longer necessary: With the removal of current restriction on any given device, the lowered function through low-frequency operation is no longer required.

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4. Continuous regeneration is possible thanks to unique bi-directional switches that connect the power supply and loads directly.
5. Greater efficiency: Only bi-directional switches link the power source and loads, permitting for more proficient operation than traditional AC Drives. Despite extensive study over the last thirty years, matrix converters have a little market share. The low input to output voltage transfer ratio of 86% has been the reason for this up to now. However, using the recently developed Z source converter design to increase the voltage transfer ratio of matrix converters is seen as a major future research task.

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Conclusion

This book is a peer reviewed project and it includes all the key topics of the current trend in power system. Hopefully, it is quite useful for research scholars and academicians, who are working in the fields of power system optimization, renewable energy integration and power electronics application in power system. It will contribute in solving many issues of modern power system.

Specific Areas of the Book Coverage:

- Global warming and climate change.
- Mitigation of energy crises.
- DC-dc microgrid,
- Application of advance controller
- Smart meters
- Smart grid.
- Modern Optimization Approaches
- Renewable energy Integration in Power System

This book is compact in size and easy to understand different dimensions of the above topics. It would be quite useful for graduate, post graduate and research scholars as they are usually looking for approach and solution in above issues in the system. Moreover, utility engineers can also refer the book for their projects in power sectors.

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