

Hemant .

plag check new 10

 major project 2

Document Details

Submission ID

trn:oid:::27535:142392280

Submission Date

Jun 10, 2026, 10:20 AM GMT+5:30

Download Date

Jun 10, 2026, 10:31 AM GMT+5:30

File Name

plag check new 10.pdf

File Size

2.9 MB

75 Pages

22,285 Words

142,059 Characters

3% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Small Matches (less than 14 words)

Match Groups

-  **33 Not Cited or Quoted 3%**
Matches with neither in-text citation nor quotation marks
-  **0 Missing Quotations 0%**
Matches that are still very similar to source material
-  **0 Missing Citation 0%**
Matches that have quotation marks, but no in-text citation
-  **0 Cited and Quoted 0%**
Matches with in-text citation present, but no quotation marks

Top Sources

- 2%  Internet sources
- 1%  Publications
- 2%  Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

Match Groups

- 33 Not Cited or Quoted 3%**
Matches with neither in-text citation nor quotation marks
- 0 Missing Quotations 0%**
Matches that are still very similar to source material
- 0 Missing Citation 0%**
Matches that have quotation marks, but no in-text citation
- 0 Cited and Quoted 0%**
Matches with in-text citation present, but no quotation marks

Top Sources

- 2% Internet sources
- 1% Publications
- 2% Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	Internet	
louisdl.louislibraries.org		<1%
2	Student papers	
AUT University on 2026-06-02		<1%
3	Internet	
jmcms.s3.amazonaws.com		<1%
4	Student papers	
University of Hertfordshire on 2026-03-27		<1%
5	Internet	
dokumen.pub		<1%
6	Student papers	
University of Strathclyde on 2026-04-02		<1%
7	Internet	
pmc.ncbi.nlm.nih.gov		<1%
8	Student papers	
Gujarat Technological University on 2026-05-06		<1%
9	Student papers	
University of Newcastle upon Tyne on 2023-10-23		<1%
10	Student papers	
University of Nottingham on 2026-03-31		<1%

11	Internet	www.chinaturbo.net	<1%
12	Student papers	I. K. Gujral Punjab Technical University on 2026-04-06	<1%
13	Student papers	University of Derby on 2026-01-15	<1%
14	Student papers	Amity University on 2016-07-24	<1%
15	Student papers	National Institute of Technology, Rourkela on 2015-05-15	<1%
16	Publication	Shuvra, Mahfuz Ali. "Grid-Friendly Services of Smart Inverter and Battery Energy ...	<1%
17	Student papers	University of Bristol on 2021-05-13	<1%
18	Internet	www.jisem-journal.com	<1%
19	Student papers	University Of Tasmania on 2011-06-06	<1%
20	Publication	Xianshun Shen, Ge Gao, Yanan Wu, Jun Qu, Zhiwei Mao, Liang Tan, Jing Lu, Mingy...	<1%
21	Internet	www.researchgate.net	<1%
22	Student papers	Gujarat Technological University on 2026-03-25	<1%
23	Student papers	Liverpool John Moores University on 2024-09-07	<1%
24	Student papers	RMIT University on 2026-05-31	<1%

25	Student papers	Singapore Institute of Technology on 2026-03-27	<1%
26	Student papers	UPN Veteran Jakarta on 2024-03-18	<1%
27	Internet	www.iieta.org	<1%
28	Internet	www.wiseguyreports.com	<1%

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF RENEWABLE ENERGY BASED MICROGRIDS

- Concept of microgrids
- Grid-connected and islanded operation
- Hybrid renewable energy systems

The high consumption of electrical energy, exhaustion of fossil fuels, and the need for environmentally friendly methods to produce electrical energy have encouraged the implementation of renewable energy sources all over the world. Traditional power systems depend on centralized electricity production using fuels like coal, oil, and natural gas. Such sources of electrical energy lead to greenhouse gas emissions that cause environmental pollution. Hence, renewable energy-based microgrids become an effective and sustainable solution.

A microgrid is considered a small-scale electrical network composed of DERs, energy storage systems, loads, and controllers that can operate in islanding or grid-connected mode. Renewable energy-based microgrids use renewable sources such as solar photovoltaic (PV) systems, wind turbines, fuel cells, small hydro-plants to produce electric energy. Moreover, they can provide power to residential, commercial, industrial, and rural areas.

To address the issue associated with intermittent renewable energy generation, hybrid renewable microgrids are implemented in combination with BESS to ensure continuity of power supply and balance between the load and generation side. Solar and wind energies depend on the solar irradiance and wind speed that leads to the generation of unbalanced and fluctuating levels of voltage, frequency, and energy. As a result, energy storage systems become indispensable for ensuring power quality and reliability in power generation.

There are certain limitations and challenges associated with renewable energy-based microgrids. Voltage sags, harmonics, and imbalanced generation lead to reduced efficiency and poor reliability. Such power quality issues need to be addressed using active power compensators such as distribution static compensators (DSTATCOM). [1] [3] [4] [12] [16] [19] [20] [21]

In order to improve the performance of hybrid renewable microgrids, DSTATCOM and energy storage can be implemented together. Such technology ensures improved efficiency and stability of microgrids based on renewable energy sources. [1] [4] [12] [14] [16] [21]

1.1.1 Global Context

The global energy industry is currently experiencing major transformations triggered by the rising need for sustainable electricity generation. Due to worries about climate change, the depletion of finite energy resources, and pollution, an increased focus has been put on harnessing renewable sources such as solar photovoltaics and wind energy conversion systems. Renewable energies have become popular since governments and power providers advocate for carbon neutral production and sustainable development.

Rapid development in the field of renewables has prompted researchers to create microgrids – local electric systems that can operate both in grid-tied and standalone configurations. In particular, hybrid renewable microgrids employ solar panels, wind turbines, diesel generator sets, and battery energy storage units to provide stable electricity. The technology has proved valuable for isolated areas, factories, cities of the future, and rural electrification programs.

Nevertheless, the use of renewable sources causes some complications that have to be addressed with appropriate measures. Solar panels and wind turbines produce unstable and inconsistent electric power. Therefore, sudden changes in irradiance and wind speed cause voltage fluctuations, harmonic distortion, reactive power imbalance, and frequency variation. All these factors affect the operation of delicate equipment and diminish the system's reliability.

Distribution Static Compensators (DSTATCOMs) can alleviate many of these issues since they have proven effective in providing dynamic reactive support and voltage control. In addition, they mitigate harmonics and balance loads. Modern research is focused on coupling the DSTATCOM systems with BESSs in order to improve the compensation and ensure additional power support.

Battery Energy-Storage-Integrated DSTATCOMs have already attracted much attention around the world since they present a viable solution for enhancing power quality and ensuring stability in power distribution systems. They contribute greatly to sustainable electricity generation.

1.1.2 Indian Context

India is considered to be among the fastest-growing energy markets in the world, and the country is rapidly progressing in the implementation of renewable energy sources to cope with the rising demand for electricity. In this regard, the Government of India is working on several initiatives such as the National Solar Mission, Green Energy Corridor Project, and Renewable Energy Development Programs. Thanks to these projects, India is considered one of the leaders in renewable energy capacity. Currently, the most popular types of renewable energy in India are solar and wind power plants.

The increasing presence of renewable energy sources in the Indian energy mix stimulated the development of hybrid renewable energy microgrids. Such power grids have been widely applied to supply electricity to the villages, commercial buildings, universities, and industries. Moreover, it should be mentioned that batteries are used in energy storage systems to stabilize renewable electricity supply.

However, there are numerous challenges associated with integrating renewable energy generators into the Indian distribution network. Thus, solar and wind energy is characterized by the presence of voltage instability, harmonic distortion, unbalance of reactive power, degradation of power factor, and changes in frequency.

In order to solve these issues, special power conditioning equipment such as the Distribution Static Compensator (DSTATCOM) is widely studied by scientists and researchers. This device helps to compensate for reactive power, mitigate harmonics, balance loads, and regulate voltage. In recent years, Indian studies focus on the application of battery energy storage in DSTATCOMs which allows generating both active and reactive power.

Given India's commitment to reaching renewable energy objectives and implementing smart grid technologies, it is obvious that BESS-DSTATCOM can help in the effective integration of renewable energy in power distribution.

Table 1.1: Global Context of Renewable Energy and Microgrids

Aspect	Global Scenario
Energy Demand	Rapid increase in electricity demand due to industrialization, urbanization, and digitalization.
Renewable Energy Growth	Significant deployment of solar PV, wind, hydro, and other renewable energy sources worldwide.
Climate Change Concerns	Global efforts to reduce greenhouse gas emissions and dependence on fossil fuels.
Smart Grid Development	Adoption of smart grid technologies for efficient power generation, transmission, and distribution.
Microgrid Deployment	Extensive implementation of grid-connected and islanded microgrids in residential, commercial, and industrial sectors.
Energy Storage Integration	Increasing use of Battery Energy Storage Systems (BESS) for energy management and grid support.
Power Quality Challenges	Voltage fluctuations, harmonic distortion, reactive power imbalance, and frequency instability due to renewable intermittency.
Advanced Compensation Devices	Deployment of DSTATCOM, STATCOM, DVR, and UPQC for power quality enhancement.
Research Trends	Development of intelligent controllers, AI-based energy management systems, and advanced synchronization techniques.
Future Focus	Sustainable energy systems, carbon neutrality, resilient microgrids, and smart energy infrastructure.

Table 1.2: Indian Context of Renewable Energy and Microgrids

Aspect	Indian Scenario
Energy Sector Growth	India is one of the world's fastest-growing electricity markets with continuously increasing energy demand.
Government Initiatives	National Solar Mission, Green Energy Corridor, PM-KUSUM Scheme, and Smart Grid Mission.
Renewable Energy Expansion	Rapid growth of solar and wind power installations across the country.
Rural Electrification	Microgrids are being deployed in remote and rural areas to improve electricity access.
Hybrid Renewable Systems	Increasing adoption of solar-wind-battery based hybrid renewable microgrids.
Battery Energy Storage	Growing implementation of BESS for peak shaving, backup power, and renewable energy integration.
Power Quality Issues	Voltage sag, voltage swell, harmonics, reactive power imbalance, and poor power factor in distribution networks.
Need for DSTATCOM	Requirement for dynamic voltage regulation, harmonic mitigation, and reactive power compensation.
Research and Development	Significant academic and industrial research on Battery Energy-Storage-Integrated DSTATCOM systems.
Future Vision	Achievement of renewable energy targets, smart grid modernization, and sustainable power distribution systems.

Table 1.3: Comparison Between Global and Indian Context

Parameter	Global Context	Indian Context
Renewable Energy Adoption	High penetration in developed countries	Rapidly growing adoption
Microgrid Development	Mature implementation in many countries	Emerging and expanding rapidly
Battery Storage Deployment	Widely integrated with renewable systems	Increasing deployment in utility and microgrid applications
Power Quality Concerns	Renewable intermittency and grid stability	Distribution network reliability and power quality improvement
DSTATCOM Applications	Advanced smart grid support	Distribution system compensation and renewable integration
Research Focus	AI-based control, smart grids, energy management	Renewable integration, power quality improvement, and cost-effective solutions
Future Goals	Carbon neutrality and energy sustainability	Renewable energy targets and smart grid development

1.2 POWER QUALITY ISSUES IN MICROGRIDS

- Voltage sag and swell
- Harmonic distortion
- Reactive power imbalance
- Frequency fluctuation
- Unbalanced loading

Power quality can be considered as the most important factor in modern electricity networks, mainly in the context of renewable energy based microgrids. The presence of distributed renewable energy generation sources like photovoltaic (PV) arrays and wind turbines raises many issues related to power quality, as they are highly nonlinear and unstable. Such disturbances can lead to the deterioration of the stability and efficiency of the microgrid. Poor power quality does not only have a negative influence on the microgrid itself, but it also poses threats to the functioning of all equipment connected to it. [4] [12] [16] [17] [21]

Voltage fluctuations caused by renewable energy generation sources pose serious threats to the quality of electricity in microgrids. Solar PV systems and wind turbines are significantly dependent on such environmental parameters as solar irradiance and wind speed, and those parameters fluctuate constantly over time. It leads to unexpected changes in power generation and, consequently, to voltage sags, swells, and instabilities in the microgrid. By voltage sag, we mean the short-term decrease in voltage magnitudes, while voltage swell means the opposite – the surge in voltages above the maximum permissible value. Voltage disturbances can be extremely dangerous for some sensitive loads and even shut down an entire industrial production process. [4] [12] [16] [20] [21]

One more important problem of the microgrid power quality is harmonic distortion caused by nonlinearity. Nonlinear loads and converters result in the appearance of harmonics in the form of distorted supply currents and voltages. Overheating, misoperation of protective elements, increased power losses, and decreased service life of equipment are the consequences of harmonics. Harmonics are characterized by THD values that can be used for evaluating their level in the network. [3] [12]

Imbalance between real and reactive power is another problem of hybrid renewable microgrids. Low reactive power in the network results in poor voltage control and poor power factors. In turn, it reduces the efficiency of electricity transmission and increases power losses. Moreover, load changes and the intermittency of the energy source generate voltage and frequency deviations, especially at the islanded mode. [12]

Disturbances related to unbalanced loads also have a negative effect on power quality in microgrids. Asymmetric distribution of the load on the three phases in the network leads to imbalanced currents, neutral currents, and extra heating in the electrical equipment. [4] [12]

The usage of compensators like DSTATCOMs, active power filters, and battery energy storage systems helps to mitigate harmonic distortions, regulate voltage and reactive power, and, thus, improve power quality. [1] [2] [3] [4] [12] [16]

1.3 DISTRIBUTED GENERATION SOURCES

1.3.1 Solar Photovoltaic System

Photovoltaic (PV) system is one of the widely applied sources of energy in present-day microgrids because they are renewable, sustainable and clean. Photovoltaic energy is a type of renewable energy which is generated through the conversion of solar irradiance into electrical energy with the help of photoelectric semiconductor material via the photoelectric effect. Due to rising environmental concerns about air pollution and scarcity of non-renewable fossil fuel, solar PV is gaining its significance as an energy source. [12][16][17]

Generally, a solar photovoltaic system comprises solar panels, power electronic converters, maximum power point trackers (MPPT), energy storage devices and control units. Solar panels comprise of a number of photovoltaic cells interconnected in series and parallel manner to produce desirable current and voltage. Upon exposure to sun, photons deliver energy to electrons in the semiconductor material resulting in production of Direct Current (DC) electricity. [17]

Output power of the solar PV system basically depends upon solar radiation, ambient temperature and characteristics of solar panels. As environmental factors constantly change during the day time, therefore, power generation also varies significantly in the system. Hence, MPPT algorithms have been applied for optimum power extraction from solar arrays depending upon their operational conditions. Popular MPPT techniques include Perturbation & Observation (P&O), Incremental Conductance (INC) and Fuzzy Logic based techniques.

For microgrid applications, DC output obtained from the solar panels has to be converted to AC by means of voltage source inverters (VSIs). In addition, power electronic converters play a key role in controlling and regulating the operation of microgrids in terms of voltage and power regulation. However, conversion process with the use of converters results in the introduction of harmonics in the microgrid power system. [3] [4][12]

There are many benefits offered by photovoltaic energy sources like low operating expenses, less maintenance, pollution free, easy and modular installation. Such systems can be applied effectively in rural and industrial areas as well as at residential places. On the other hand, intermittency of solar energy gives rise to several challenges for microgrids in the form of fluctuations in voltage, frequency and power. [14] [21]

It has been suggested that for enhancing the performance and efficiency of renewable microgrids, solar PV should be combined with battery energy storage systems as well as compensation devices such as DSTATCOMs. [1][4][12][16][21]

1.3.2 Wind Energy Conversion System

Wind Energy Conversion Systems (WECS) play a vital role in renewable energy based microgrids by converting the kinetic energy of wind into electrical energy. Due to the increasing demand for clean and sustainable energy sources, wind power generation has become one of the fastest-growing renewable energy technologies worldwide. Wind

energy systems are widely integrated into hybrid renewable microgrids to enhance energy availability and reduce dependence on conventional fossil fuel based generation. [12] [16]

A typical wind energy conversion system consists of a wind turbine, gearbox, generator, power electronic converters, controllers, and protection systems. The wind turbine captures the kinetic energy of moving air through rotating blades and converts it into mechanical energy. This mechanical energy is then transferred to an electrical generator to produce electrical power. Depending on the design, wind turbines may operate at fixed speed or variable speed conditions.

The amount of power that a wind turbine can generate is directly related to wind velocity, air density, rotor radius, and the efficiency of the system. Due to the continuous variability in the wind speed, the generated power from WECS varies considerably as well. Wind power generation is directly proportional to the cubic value of wind velocity. Hence, even minute fluctuations in wind speed have a significant effect on power generation. [16] [21]

Wind energy systems utilize either synchronous generators or induction generators coupled with converters. These converters play an important role in controlling voltage and power flows along with achieving synchronization with the microgrid. Variable speed wind turbines with efficient control methods can provide better performance in terms of enhanced efficiency, reduced stress, and high-quality performance. [4] [12]

Though there are many environmental and economical benefits associated with wind energy systems, yet, these systems are responsible for bringing about some technical challenges for microgrids. The unpredictable and intermittent nature of wind results in voltage fluctuation, frequency change, and power imbalance in the electrical network. Moreover, the switching mechanism of converters as well as nonlinear loads leads to harmonics which ultimately affect power quality by causing problems like high THD, voltage fluctuations, and low power factor. [3] [4] [12] [21]

For making hybrid renewable microgrids more stable and reliable, BESS and DSTATCOM are often employed alongside WECS. The incorporation of BESS provides flexibility in managing power fluctuations due to abrupt changes in wind speed, while DSTATCOM acts as a source of reactive power, harmonic elimination, and voltage regulation. The combination of these components considerably improves the performance and power quality of hybrid renewable microgrids. [1] [3] [4] [12] [16] [21]

1.3.3 Fuel Cell / Diesel Backup System

Fuel cells and diesel generators can be implemented as backup resources to ensure constant availability in case of energy production deficiency from renewable resources. Actually, energy resources like solar photovoltaic energy and wind power are intermittent sources, which require the usage of some additional sources to keep the stability of voltage, energy supply, and system operation. Extra energy generation with the help of fuel cells and diesel generators may be needed due to low solar radiation, low wind speed, rapid load change, and other situations. [12] [16] [17] [21]

Fuel cell technology provides the possibility of converting chemical energy directly into electric energy without any combustion process. Hydrogen is one of the most common fuels that can be used in fuel cells. Fuel cells are based on the electrochemical reactions of hydrogen and oxygen with the production of electricity, heat, and water. Advantages of fuel cells include efficiency, quiet operation, small amount of emissions, and reliability of the process. PEMFC fuel cells are usually implemented in microgrids because of fast response, compactness, and low operating temperatures. [12]

In general, a fuel cell system should consist of several parts, including the following: fuel processor, fuel cell stack, DC-DC converter, inverter, and control system. It is crucial to note that voltage produced by fuel cells is quite low, but depends on load conditions. Therefore, implementation of power electronics in the fuel cell system becomes necessary to increase the voltage level. Fuel cells also generate electricity, which is quite stable, and suitable for supporting important loads. [12]

There is yet another supplementary system that is used in hybrid renewable microgrids as an emergency source. Diesel generators are the devices generating electric energy according to the principle of converting chemical energy to mechanical energy with the help of internal combustion engine and further transformation into electric with the help of alternators. The advantages of diesel generators are represented by reliability and possibility to supply electric energy on a massive scale. [12] [16]

Nevertheless, there are also some disadvantages related to diesel generators including dependency on fuel, greenhouse gases emission, noise pollution, and expensive operations. Compared to fuel cells, they operate noisily and not very environmentally friendly, but are more affordable for the implementation and maintenance than fuel cells. Consequently, renewable microgrids are usually implemented as a combination of renewable energy resources, batteries, fuel cells, and diesel generators. [12] [16]

Combination of diesel generators and fuel cells with DSTATCOM and battery energy storage makes it possible to stabilize a microgrid system because of providing more functions to it. [1] [3] [12] [21]

1.4 ENERGY STORAGE SYSTEMS IN MICROGRIDS

- Need for battery storage
- Types of battery technologies
- State of Charge (SOC) considerations
- Battery management system

Energy Storage Systems (ESS) are critical components of modern renewable energy based microgrids as they play an important role in maintaining balance between power generation and consumption, increasing reliability and efficiency of the system. Renewable energy sources including solar photovoltaic (PV) and wind energy are highly variable and highly dependable on weather conditions. Therefore, energy storage is necessary for storing energy that was generated in excess and for supplying power in case of insufficient renewable power production or high load demands. [12] [16] [17]

In hybrid renewable microgrids, fluctuations in solar irradiance and wind speed cause fluctuations in voltage, frequency and power. Such fluctuations may be associated with instability and poor power quality within the system. With energy storage systems installed, it will become possible to mitigate negative consequences of power fluctuations caused by natural causes through flexible power control. Excess electricity will be stored at times of high power generation and utilized at times of low power generation and high demand. [4] [12] [21]

Battery Energy Storage Systems (BESS) are currently the most common type of storage used in microgrid applications due to high efficiency, quick reaction time, small size, and easy incorporation with power electronic converters. Battery types commonly used include lead-acid batteries, lithium-ion batteries, nickel-cadmium batteries and flow batteries. Of all the types mentioned above, lithium-ion batteries have been gaining more popularity due to their high capacity, long life time, low maintenance requirements and good charging capability. [12]

Operation of BESS depends on the charging and discharging process according to system conditions and State of Charge (SOC). At times of excessive power generation, batteries are charged and energy is stored in them in the form of chemistry. At times of high demand or insufficient renewable generation, electricity is restored from batteries. For monitoring batteries condition during operation and managing charging and discharging processes, special battery management systems (BMS) that measure voltage, current, temperature, and SOC are used. [12]

ESS is also important for power quality improvement purposes. ESS is used for voltage regulation, frequency control, load leveling, peak shaving, and harmonics removal. Combining ESS with compensation devices like distribution static compensators (DSTATCOMs) ensures provision of advanced reactive power support and compensation control capabilities. [1] [3] [4]

The installation of ESS in renewable energy based microgrids improves reliability of the systems, enhances utilization of renewable energy, minimizes the dependence on conventional energy sources, and promotes the development of sustainable smart grids. [12] [14] [16]

1.5 FUNDAMENTALS OF DSTATCOM

- Operating principle
- Reactive power compensation
- Harmonic mitigation [3]
- Voltage regulation capability

Distribution Static Compensator or DSTATCOM is an efficient compensating device used in many modern distribution systems and renewable energy-based microgrids for power quality improvement. It is considered as one of the most efficient custom power devices used for reactive power compensation, harmonics elimination, voltage regulation, and loading balancing in electrical distribution networks. Increasing the penetration level

of nonlinear loads and renewable energy sources in modern electricity networks has led to the importance of this device. [1] [3] [4] [12] [16] [21]

A DSTATCOM includes the Voltage Source Converter (VSC), a DC-link capacitor, a transformer or coupling inductor, harmonic filter, and control section. The main function of the VSC is to produce a controllable voltage source from the energy provided in the form of DC source. A capacitor is used to act as an energy storage device and provide the necessary DC link voltage for VSC. [1] [3]

Operation of the DSTATCOM depends on the reactive power exchange between the compensator and distribution system. By controlling the magnitude and phase angle of the output voltage produced from the VSC, reactive power can be supplied or absorbed by the device. In the case of having a higher voltage at the converter output compared to the system voltage, reactive power will be supplied, and vice versa. [1] [21]

High effectiveness in solving the existing power quality problems associated with the use of nonlinear loads and renewable energy sources makes the DSTATCOM highly important. Harmonics compensation of the currents produced by power electronics converters leads to minimizing the THD factor in the system. Moreover, the compensator solves problems related to voltage sags, swells, flickers, and unbalanced loadings in the system. [1] [3] [4] [16] [20]

In renewable energy-based hybrid microgrids, the voltage stabilization process during fluctuation of the renewable sources in generating capacity can be effectively done using DSTATCOM. Also, integration of BESS in the system makes it possible to provide better dynamics of this compensator by producing active power support. [1] [12] [16]

Compared to traditional compensation devices such as capacitors or synchronous condensers, a DSTATCOM possesses high efficiency and compact design. High response time of this compensator, together with high reliability, makes it highly desirable for application in modern smart grids, distributed generation, and renewable microgrids. [1] [4] [12] [14]

1.6 BATTERY ENERGY STORAGE INTEGRATED DSTATCOM

- Combined operation
- Advantages over conventional DSTATCOM [1]
- Role in renewable intermittency mitigation

The integration of Battery Energy Storage System (BESS) and Distribution Static Compensator (DSTATCOM) is considered as one of the most sophisticated solutions for improving power quality and increasing stability of power networks with renewable energy-based hybrid microgrids. Solar photovoltaic and wind energy are among the widely used renewable energy sources. However, their output is characterized by considerable intermittence caused by changing environmental conditions. Such changes result in instability in voltage, frequency, and power flow, thus affecting the performance and reliability of a microgrid. Therefore, integration of DSTATCOM and BESS allows

overcoming these limitations through providing both active and reactive compensation. [1] [4] [12] [16] [17] [21]

Battery Energy Storage Integrated DSTATCOM system integrates two separate functions – reactive power compensation of DSTATCOM and active energy storage of a battery system. The battery operates as part of the DC-link of the Voltage Source Converter (VSC), which includes suitable converters between these elements. While DSTATCOM provides reactive power compensation, filters harmonic distortions, and controls voltage, BESS absorbs surplus energy from renewable energy sources or returns it back to the system depending on the operation mode of a microgrid. [1] [3] [12]

Thus, during peak power generation from renewable sources, the storage of energy in batteries is performed in order to provide the additional energy for supporting power balance during peak loads or low power production. Such operation ensures increased dynamics and stability of the microgrid. [12] [21]

Battery Energy Storage Integrated DSTATCOM system successfully solves such problems related to power quality as voltage sags and swells, harmonics, reactive power imbalance, and frequency changes. DSTATCOM injects reactive currents that help lower THD levels and improve power factor, whereas BESS compensates for active energy. [1] [3] [4] [20]

Synchronous Reference Frame (SRF) theory, hysteresis current control, fuzzy logic control, and PI-based controllers are often used in the control of Battery Energy Storage Integrated DSTATCOM systems. With the help of these controllers, it is possible to achieve high-accuracy reference current generation and efficient compensation performance. [1]

It is also necessary to mention advantages of using Battery Energy Storage Integrated DSTATCOM compared to traditional compensation technologies, including higher speed of response, increased voltage stability, improved usage of renewable energy sources, lower power losses, and stable operation during grid disturbances. Consequently, the integration of DSTATCOM with BESS became a necessity in modern smart grids and distributed generation systems, which aim to improve power quality and manage renewable energy. [1] [4] [12] [14] [16] [21]

1.7 POWER ELECTRONIC CONVERTERS USED IN DSTATCOM

1.7.1 Voltage Source Converter (VSC)

VSC stands for the Voltage Source Converter which is one of the basic units of the Distribution Static Compensator. Moreover, the VSC is the main constituent of the DSTATCOM which contributes greatly to the quality improvement of electric power delivered via renewable energy based microgrids. A Voltage Source Converter is a power electronics device which generates an AC signal having predefined parameters. In particular, the amplitude, frequency and phase angle of the signal generated by the converter are adjustable. The Voltage Source Converter serves as an interface between the DC energy source or battery and the AC network. [1] [4] [12] [16]

In the DSTATCOM, the VSC is employed as the main device producing compensating currents necessary for supporting the reactive power, mitigating harmonic distortions, and stabilizing the voltage level of the electrical grid. As mentioned above, the VSC utilizes high-frequency semiconductor switching devices such as IGBTs, MOSFETs or GTO thyristors which should be triggered according to certain algorithms resulting in the creation of AC voltage waves from the DC-link voltage. [1] [3]

A standard Voltage Source Converter includes such components as the DC-link capacitor, switching devices connected in bridge configuration, driving and gating circuits, and coupling inductors/transformers. The DC-link capacitor maintains the DC link voltage constant and provides temporary energy storage function. The AC voltage generated by the VSC is supplied to the electrical grid via coupling inductors controlling the AC current flowing in the circuit. [3]

The operating principles of the VSC are based on using the pulse width modulation technology in which the switching pulses determine the AC voltage wave parameters such as frequency and amplitude. As a result, the converter makes it possible to regulate both active and reactive powers exchanged between the DSTATCOM and power network. With the integration of the battery, the converter is able to compensate the energy exchange with the power system during transient processes or fluctuations in renewable energy resources. [1]

When used in the context of renewable energy based microgrids, the VSCs serve a number of essential purposes including harmonic compensation, load balancing, voltage stabilization and power factor improvement. Moreover, due to its high efficiency, the VSC ensures fast dynamic response under changing load and generation conditions and is capable of operation in two modes of a microgrid – isolated or grid-connected mode. [1] [3] [12] [16] [19]

As compared to traditional converters, the VSC offers a number of advantages such as smaller size, higher efficiency, improved control ability, lower harmonics content and higher reaction rate. Thanks to all these factors, the Voltage Source Converter is widely applied in modern power electronic equipment including DSTATCOM, renewable energy based systems, smart grids and other devices aimed at improving power quality. [1] [3] [4] [14] [16]

1.7.2 PWM Techniques

The use of Pulse Width Modulation (PWM) methods in DSTATCOM systems is prevalent when it comes to regulating the working conditions of power converters. PWM is described as a modulation approach where a varying switching pulse width is used to create a certain output voltage, while the frequency remains constant. PWM is extremely beneficial in improving the efficiency of VSC based DSTATCOMs, especially in relation to renewable energy. [1] [4] [12] [16]

In a DSTATCOM system, various techniques of PWM are employed in order to create specific gating signals for semiconductor switches such as IGBT and MOSFET employed in VSC. Through the process of controlling the switching process, the converter

creates AC output voltage with a predetermined magnitude, frequency, and phase angle, hence providing an opportunity for effective power compensation in the system. [1] [3]

Sinusoidal Pulse Width Modulation (SPWM) is one of the most commonly used PWM techniques that involve comparison of sinusoidal reference signal and high-frequency triangular signal to produce a set of switching pulses. The width of the output pulse varies with the reference sine wave amplitude to generate the required sine output waveform. SPWM is popular since it has been found to be fairly straightforward and simple to apply. [3]

Space Vector Pulse Width Modulation (SVPWM) is another commonly applied technique for PWM. As opposed to the conventional SPWM technique, SVPWM increases efficiency since it involves use of DC-link voltage. SVPWM works through the application of vector switching states to generate the desirable output voltage vector. [3]

Apart from being used in conjunction with VSC in a DSTATCOM system, Hysteresis Current Control is among the widely used PWM techniques that help maintain a desirable degree of harmonics in the system. According to HCC technique, the current in question is measured and compared against a particular reference current level. [1] [3] [19]

Some of the benefits associated with use of PWM techniques in a DSTATCOM include a significant reduction in Total Harmonic Distortion (THD) and improvement in power quality of microgrid. PWM techniques provide an opportunity for precise control of both active and reactive power in the system. Moreover, advanced PWM techniques have contributed immensely to reduced switching losses in converters. [1] [3] [4] [12]

Given the advantages mentioned above, PWM techniques can easily be recommended for application in various power electronic systems including DSTATCOM systems.

1.7.3 DC-Link Capacitor

The DC-link capacitor is a critical element of Voltage Source Converters used in DSTATCOM based systems and has an essential role in maintaining stable operation of the converter in renewable energy based microgrids. The DC-link capacitor is positioned across the DC side of the converter and functions as a power storage element used for voltage stabilization and power balancing in dynamic modes. [1] [12] [16]

To operate correctly, Voltage Source Converter used in a DSTATCOM-based system needs constant DC voltage for generating AC compensating voltage. The capacitor in charge of maintaining stable DC voltage in such converters. Fluctuations and changes in the amount of load, renewable energy production, and switch operations might affect DC-link voltage and need to be compensated using stored energy by the DC-link capacitor. [1] [16]

DC-link capacitor operation is based on energy storage and releasing capabilities due to the electric field formation. If there is excess energy present in the power circuit, it gets stored in the capacitor. In case of temporary disturbance and voltage drop due to it, capacitor discharges accumulated energy and maintains stable DC-link voltage levels.

Such behavior of the DC-link capacitor makes it possible to provide constant reactive power compensation and eliminate harmonics. [1] [3]

In systems where DSTATCOM works together with the battery energy storage element, the DC-link capacitor is a key element in stabilizing and optimizing the operation of such systems. As the battery provides long-duration energy for the operation of the system, the capacitor is responsible for short-duration voltage fluctuations compensation and disturbance elimination. [1] [4] [12] [21]

Selection of DC-link capacitor value depends on many factors and is highly important for correct operation of converter-based equipment. Incorrect choice of capacitor value can lead to either too much voltage ripple or increased cost and space consumption. Proper capacitor value can be selected based on system power rating, switching frequency, allowed voltage ripple, and system dynamic response.

Another important advantage of the use of the DC-link capacitor in power systems is the reduction of voltage harmonics due to the possibility of maintaining stable DC voltage and, consequently, performing efficient PWM switching and reactive currents generation. Moreover, the capacitor acts as protection for semiconductor switch units from any abrupt change of current and voltage levels. [3]

Thus, due to its fast energy storage and DC voltage stabilization capabilities, the DC-link capacitor can be considered one of the most critical elements of DSTATCOM-based, renewable energy conversion, motor drive, FACTS, and smart grid systems. [1] [4] [14] [16]

1.8 CONTROL TECHNIQUES FOR DSTATCOM

- PI controller
- SRF theory
- Hysteresis current control
- Fuzzy logic control
- Adaptive control methods

Control techniques are highly important for successful operation of the DSTATCOM devices applied in renewable energy based microgrids. It should be stressed that a large amount of the DSTATCOM effectiveness greatly depends on the applied control approach. Control techniques are responsible for reference compensating currents, DC-link voltage control, control of reactive power flow, and compensation of harmonics in distribution network. [1] [3] [4] [12] [16]

It should be emphasized that the Proportional-Integral (PI) controller is widely applied as one of the basic control techniques in the DSTATCOM systems. This controller controls DC-link voltage, reduces steady-state errors and compares the actual and reference values constantly. Thus, the application of the PI controller implies its simplicity and satisfactory performance characteristics under normal conditions. At the same time, the mentioned control approach may demonstrate decreased results during nonlinear and rapidly changing process. [1]

Another widely used control technique is the synchronous reference frame (SRF) theory, which implies transformation of three-phase AC quantities to d-q reference frames through Park's transformation. In other words, the application of this technique provides independence in control of the active and reactive power components leading to precise harmonics compensation and voltages control. High precision and fast response to system changes are the main benefits of SRF control. That is why this technique is widely used today. [1] [3] [12] [19]

Hysteresis Current Control (HCC) is often applied for generation of switching pulses in VSC. This control technique is characterized by continuous comparison of the actual current to the reference current within hysteresis bands. In case of exceeding the specified bands, switching actions are started ensuring precise current tracking. Fast dynamic response and high effectiveness of harmonics compensation are two advantages of HCC. However, this approach causes unpredictable switching frequencies. [3]

Fuzzy Logic Controllers (FLC) are widely discussed today due to their capability to provide proper system control in case of nonlinear and uncertain conditions regardless of the absence of the accurate mathematical model. Linguistic rules and membership functions are used by FLCs for making control decisions depending on system performance. High level of robustness, reduced overshoot and improved stability are the major advantages of this control approach. [16] [21]

Such advanced control approaches as Artificial Neural Networks (ANN), Particle Swarm Optimization (PSO), and Model Predictive Control (MPC) attract researchers' attention today. Enhanced accuracy, adaptability, and efficient compensation of power in complex hybrid renewable microgrids can be obtained with their application. [1] [8] [12]

The choice of adequate control technique is determined by several parameters including system complexity, response speed, computational demands, etc. Adequate control techniques positively affect performance of BESS integrated DSTATCOM systems. [1] [4] [14] [21]

1.9 IMPORTANCE OF POWER QUALITY IMPROVEMENT [4]

- Industrial applications
- Grid stability [21]
- Reliability enhancement

Nowadays, there has been a growing focus on enhancing power quality due to its critical importance in renewable energy based microgrids. Power quality denotes providing a stable voltage, frequency, and sinusoidal wave form of voltage. In addition to the above mentioned factors, power quality requires a consistent supply of the energy source, and it is defined by the extent to which voltage and frequency variations lie within tolerable levels. Any deviation from acceptable voltage, frequency, and sinusoidal wave form of the supplied electricity leads to failure of equipment, increases power losses, and causes interruption of vital industrial and commercial activities. [4] [12] [16]

Introducing renewable energy sources such as solar PV systems and wind energy converters has created many issues concerning power quality including voltage sags, harmonics, reactive power imbalance, and frequency instability. Considering that power generated by renewable energy sources is very much prone to weather conditions, the output power from renewable energy sources varies with respect to time, causing severe problems with power quality. Hence, power quality improvement has become one of the important considerations when designing power systems. [3] [4] [12] [16] [17] [21]

The first important reason behind the implementation of effective power quality improvement methods and devices is to protect sensitive electrical devices and equipment. Many advanced industrial systems, medical equipment, communication devices, and automation devices are highly sensitive to any changes in the power quality. Voltage sag, voltage swell, harmonics, and other disturbances might affect sensitive devices and cause failure in their normal functioning. Proper implementation of power quality improvement strategies minimizes the effect of the power quality disturbances. [3] [4] [20]

Reducing Total Harmonic Distortion (THD) and eliminating harmonics have become crucial aspects in improving the power quality. Power electronic converters, non-linear loads, and switch mode devices produce harmonics that affect the voltage and current wave forms, increasing thermal losses in motors, transformers, and transmission lines. Power quality improvement ensures low levels of THD and harmonics. [3] [4]

Another vital issue in power quality improvement lies in the proper control of reactive power. The power factor and reactive power imbalance may create problems with efficiency and stability during power transmission and distribution. For example, DSTATCOM acts as a device which improves voltage profiles, reduces transmission losses, and provides fast reactive power support to the network. [1] [21]

In addition, in a hybrid renewable energy based microgrid, power quality improvement helps in achieving stable power transmission and efficient utilization of renewable energy sources in both grid-connected and islanded modes of operation. Incorporating battery energy storage systems into DSTATCOM provides better power quality during transient events. [1] [4] [12] [16] [21]

Thus, power quality improvement is important not only in achieving stable power transmission but also in minimizing losses and protecting the equipment in modern smart grids and hybrid renewable microgrids. [4] [12] [14]

1.10 PROBLEM STATEMENT

Integrating renewable energy sources such as solar PV systems and wind energy conversion systems into current microgrids has introduced a number of technical problems concerning power quality and system stability. Although hybrid renewable microgrids help to protect the environment and minimize the use of traditional forms of energy, i.e. fossil fuel generation, their irregularity and unpredictability cause considerable variation in voltage, frequency, and power flow that negatively impacts the effectiveness of the electrical distribution system. [4] [12] [16] [17] [21]

A nonlinear character of loads used in hybrid renewable microgrids together with power electronics converters for integration of renewable energy lead to generation of harmonics and reactive power imbalance. These factors contribute to the creation of poor power factor, increased total harmonic distortion, voltage sag and swell, unbalance loading, and unstable frequency. The presence of such power quality problems can cause overheating of devices, failures in the operation of sensitive instruments, additional losses in the process of power transmission, and decreased lifetime of equipment components. [3] [4] [12] [16] [20] [21]

Traditional approaches to power quality improvement and compensation of reactive power, i.e. the use of capacitor banks and passive filters, cannot be effectively applied to the operation of modern renewable energy sources due to the lack of flexibility. These traditional approaches are characterized by a slow dynamic response, fixed compensation ability, the risk of resonance, and poor performance at variable operating conditions. For this reason, more advanced compensation devices with faster response and better adjustment ability should be developed. [12] [16]

Distribution Static Compensator (DSTATCOM) is an effective technique for reactive power compensation, elimination of harmonics and voltage regulation in distribution systems. However, conventional DSTATCOM systems have only the ability to compensate reactive power, whereas its potential ability to manage fluctuating active power of the intermittent nature remains limited. Integrating Battery Energy Storage Systems (BESS) into DSTATCOM systems provides an opportunity to compensate simultaneously reactive and active power variations. [1] [3] [16]

Although using BESS with DSTATCOM brings a number of advantages in terms of providing improved power quality and compensation of active and reactive power, certain problems remain unsolved in relation to the control efficiency, fast dynamic response, stable DC-link voltage regulation, and harmonic elimination. That is why it is essential to create an efficient control strategy for BESS-integrated DSTATCOM. [1] [3] [4] [12] [19] [21]

1.11 OBJECTIVES OF THE THESIS

The first objective of the present thesis is to develop and evaluate a Battery Energy-Storage-Integrated Distribution Static Compensator (DSTATCOM) for improving power quality and increasing stability of hybrid renewable energy-based microgrids. This project proposes to compensate different power quality disturbances arising due to the intermittent nature of renewable energy resources and the presence of nonlinear loads. [1] [4] [12] [16] [21]

The specific objectives of the present work are listed below.

1. To study the behavior and characteristics of hybrid renewable energy based microgrids including solar PV systems, wind energy conversion systems, and battery energy storage systems. [12] [16] [17]
2. To identify and study different power quality problems like voltage sag, voltage swell, harmonic distortion, reactive power imbalance, low power factor, and

- frequency instability encountered in renewable energy based microgrids. [3] [4] [12] [16] [20] [21]
3. To study the working principle and compensatory ability of Distribution Static Compensator (DSTATCOM) for providing reactive power support and reducing harmonics. [1] [3]
 4. To design and develop a model of Battery Energy Storage Integrated DSTATCOM system for active/reactive power compensation of hybrid renewable microgrids. [1] [12]
 5. To formulate an effective control algorithm for the designed DSTATCOM system utilizing suitable control algorithms for the precise generation of reference current and regulating DC-link voltage. [1]
 6. To minimize THD and improve the power factor of the microgrid. [3] [12]
 7. To increase voltage stability and provide balanced microgrid operation under varying load conditions and renewable generation fluctuations. [12] [21]
 8. To evaluate the dynamic behavior of the developed DSTATCOM system under different operational modes like grid-connected mode, islanding mode, nonlinear loading, and renewable power fluctuations.
 9. To simulate the proposed Battery Energy-Storage-Integrated DSTATCOM system through MATLAB/Simulink platform and analyze its performance. [1]
 10. To compare the performance of the proposed DSTATCOM with traditional compensation schemes in terms of improvement in power quality, voltage regulation, harmonic suppression, and microgrid stability. [3] [4] [21]

Achieving these above-stated objectives would help us to propose an efficient power quality enhancement methodology for modern renewable microgrids. [4] [12] [14]

1.12 SCOPE OF THE WORK

The scope of the current work revolves around design, modeling, control, and performance evaluation of a Battery Energy Storage Integrated Distribution Static Compensator (DSTATCOM) for power quality enhancement in hybrid renewable energy-based microgrids. The present work primarily addresses the problems faced due to the use of renewable energy sources that are mostly unstable and pose serious concerns regarding voltage, harmonics, reactive power imbalance, and fluctuating power generation from intermittent sources. [1] [3] [4] [12] [16] [21]

In the current project, the hybrid renewable microgrid system consists of solar PV systems, wind energy conversion systems, battery energy storage systems (BESS), nonlinear loads, and utility grid interfacing. The main aim of integrating a battery energy storage with DSTATCOM is to enhance the active and reactive power compensation of the system. [1] [12] [17] [21]

This research project entails the mathematical modeling and simulation of renewable energy sources, battery energy storage systems, voltage source converter, DC link capacitor, and DSTATCOM controller system. Proper control techniques would be incorporated to produce compensating reference currents, regulate DC link voltage, and optimize the dynamic performance of the system. The proposed controller is intended to

minimize the total harmonic distortion, enhance the power factor, stabilize the voltage, and address various power quality disturbances. [1] [3] [4] [16]

The current project would involve simulation analysis using the MATLAB/Simulink software platform. Several scenarios have been included in the study for the purposes of analyzing and evaluating the performance of the proposed model. This would involve simulating the behavior of the system in case of nonlinear loading conditions, sudden load changes, fluctuations in the renewable power generation, and transients. Analysis of the proposed model would also incorporate the simulation of performance under normal conditions, with and without BES-DSTATCOM installation. [1]

In the current work, low voltage microgrid level application is targeted while hardware implementations and experimental analysis are out of scope. Economic analysis, communication systems, cyber security analysis, and battery aging analysis do not form part of this research project. [12]

However, the current project forms a basis for further research works in relation to real-time implementation, advanced intelligence controllers, hardware-in-the-loop analysis, electric vehicle integration, and smart grids applications. [4] [12] [14] [16] [21]

1.13 ORGANIZATION OF THE THESIS

The thesis is divided into five chapters covering various aspects of the proposed Battery Energy-Storage-Integrated DSTATCOM for power quality improvement in hybrid renewable microgrids. The chapter-wise structure of the thesis is as follows: [1] [4] [12]

Chapter 1: Introduction

This chapter introduces the basic concepts related to renewable energy based microgrids and their significance in terms of power quality improvement in electrical distribution systems. An introduction to solar photovoltaic systems, wind energy conversion systems, battery energy storage systems and Distribution Static Compensator (DSTATCOM) is provided. This chapter also covers major power quality problems faced by renewable energy integrated microgrids, motivations behind the work, problem statements, objectives and scope of the thesis. [1] [4] [12] [16] [17]

Chapter 2: Literature Review

This chapter consists of detailed review of existing research work on the topic of power quality improvement, renewable energy integrated microgrids, applications of DSTATCOM and battery energy storage systems. Different control algorithms and compensation techniques used in literature are reviewed and analyzed. This chapter also identifies important research gaps and points out the need of developing an efficient Battery Energy-Storage-Integrated DSTATCOM. [1] [4] [12] [16]

Chapter 3: System Modeling and Proposed Methodology

This chapter discusses the modeling and design process of the proposed hybrid renewable microgrid system. Mathematical models of solar photovoltaic system, wind energy conversion system, battery energy storage system and DSTATCOM are described. Operating principle, control approach, reference current generation technique and DC-link voltage control strategy of the proposed Battery Energy-Storage-Integrated DSTATCOM are explained. Details regarding the implementation of the system in MATLAB/Simulink environment are also presented. [1] [12] [17]

Chapter 4: Simulation Results and Discussion

Simulation analysis and performance evaluations of the proposed system are covered in this chapter. Performance of the Battery Energy-Storage-Integrated DSTATCOM in reducing harmonics, reactive power compensation, voltage profile improvement and stabilization of microgrid is evaluated. Comparative analysis between compensated and uncompensated systems is discussed through simulations. [1] [3] [12]

Chapter 5: Future Scope and Conclusion

This chapter concludes the important findings and contributions made in this work. Effectiveness of the proposed system in power quality improvement and enhanced microgrid stability is highlighted. Limitations of the present work are also stated and potential future research directions for further investigation are suggested including intelligent control, hardware implementation and smart grids application. [4] [12] [14] [21]

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW OF EXISTING MICROGRID ARCHITECTURES

A microgrid is a small-scale local power generation and distribution system composed of distributed energy resources, energy storage systems, power electronics converters, and end-use loads. It can function either as a grid-connected microgrid or an islanded microgrid based on specific requirements and availability of the grid. The growing presence of renewable energy resources like solar PV systems and wind energy conversion systems has tremendously facilitated the growth of hybrid renewable microgrids. [12] [16] [17]

The microgrids are basically categorized as AC microgrids, DC microgrids, and hybrid AC/DC microgrids. AC microgrids comprise all distributed generators and loads being interconnected through a common AC bus. But AC microgrids experience certain issues related to reactive power imbalances, harmonics, and voltage instabilities because of nonlinear loads and intermittent renewable energy sources. [3] [12] [16]

DC microgrids involve a common DC bus to integrate the renewable energy sources and batteries. Since solar PV systems and battery storage units generate DC power, DC microgrids have a high efficiency level compared to other microgrids. They require complicated protection mechanisms along with special interfacing converters for grid integration. [12] [16]

Hybrid AC/DC microgrids involve connecting AC and DC buses through converters and thus take advantage of both AC and DC microgrids' benefits. Hybrid AC/DC microgrids provide greater flexibility and improve the efficient utilization of renewable energy sources and storage systems. [12] [16]

The microgrids can also function as grid-connected or islanded microgrids. Grid-connected microgrids receive assistance from the utility grid in case of power imbalance in the microgrid, whereas islanded microgrids need to operate independently without any grid assistance and thus ensure stable voltage and frequency levels in the system. [12] [21]

However, some challenges exist in the conventional microgrids concerning the issues of harmonics, voltage instabilities, intermittence in renewable energy generation, and reactive power imbalances. Advanced compensation systems like Battery Energy Storage Integrated DSTATCOMs are used to solve such challenges. [1] [3] [4] [12] [21]

2.2 REVIEW OF POWER QUALITY ENHANCEMENT TECHNIQUES

The concept of power quality improvement is becoming highly popular these days, owing to the integration of renewable energy sources and power electronic converters into power

systems. Poor power quality leads to voltage sag, voltage swell, harmonic distortions, reactive power imbalance, voltage flicker, and frequency fluctuations which impact the reliability and performance of power systems. Therefore, there are many compensation schemes introduced for power quality improvements in microgrids and distribution systems. [3] [4] [12] [16] [20] [21]

There are various conventional compensation schemes such as passive filter, capacitor bank, and synchronous condenser that are used for compensation. Passive filters are used for harmonic filtering as they have a relatively simple configuration and are inexpensive. However, these are affected by resonances, provide fixed compensation capabilities and lack dynamic compensation capability with changing loads. Capacitor banks are commonly used for reactive power and voltage compensation but cannot compensate harmonics and transients. [3]

Advanced power electronic converter based compensation techniques such as Active Power Filters (APF), Static VAR Compensators (SVC) and Distribution Static Compensators (DSTATCOMs) have also been introduced for compensation. DSTATCOM is considered as an efficient device to compensate for various types of power quality issues in the integrated microgrids with renewable energy sources. This device is capable of fast dynamic response, harmonic compensation, reactive power compensation, load balance and voltage regulation. [1] [2] [3] [4] [12] [16]

Various control algorithms have been developed for controlling the operation of DSTATCOM. Some examples include Synchronous Reference Frame (SRF) based control, instantaneous p-q control, hysteresis current control, fuzzy logic control and artificial neural network based controller. Such advanced control algorithms enhance the compensation capability of DSTATCOMs for achieving stability and improved performance. [1] [21]

In recent years, various DSTATCOM configurations integrated with battery energy storage system (BESS) have been introduced to cater for power quality improvement requirements of renewable energy based microgrids. Integration of BESS further enhances system stability, active power flow and compensation capacity. [1] [12] [16] [21]

Therefore, advanced power quality improvement schemes use intelligent control systems along with energy storage integrated compensators. [4] [12]

2.3 LITERATURE ON DSTATCOM APPLICATIONS

- Reactive power compensation
- Harmonic elimination [3]
- Load balancing

Distribution Static Compensator (DSTATCOM) has become one of the most effective custom power devices for power quality improvement in the modern era. It can be employed for reactive power compensation, harmonic mitigation, voltage regulation, load balancing, and stabilization of the distribution system. Because of the fast dynamic

response and flexible nature of the control system, DSTATCOM has become very prominent in modern smart grids and microgrids applications. [1] [3] [4] [12] [14] [16] [21]

Different researches have been performed to show the potential of DSTATCOM for power quality improvement. Singh and Sharma introduced four-leg voltage source converter (VSC)-based DSTATCOM for use in autonomous wind energy conversion systems and observed successful results regarding the voltage regulation and reactive power compensation. On the other hand, Zaveri et al. explained various control strategies of DSTATCOM to minimize the harmonics and ensure high-quality source current. [1] [3] [4]

Most recent research works on the application of DSTATCOM have discussed integration of BESS and renewable sources. Mahela and Shaik showed that integration of BESS with DSTATCOM can significantly enhance voltage stability and lead to the reduction of Total Harmonic Distortion (THD). Wang et al. also explained the benefits of using DSTATCOM for power quality improvement in energy-storage-based systems. [1] [3] [16] [21]

Some intelligent control techniques like SRF Theory, fuzzy logic control, adaptive control, artificial neural networks (ANN), and ANFIS-based controllers have also been suggested for enhancement of DSTATCOM performance. They include fast reference current generation and harmonic mitigation even under nonlinear load condition due to their intelligence. [1] [3] [8] [19]

The applications of DSTATCOM are not limited to distribution networks but are also utilized in Photovoltaic-Wind Integrated Microgrid for ensuring stable operation even at time of fluctuating renewable power production. The inclusion of BESS in DSTATCOM improves its active power handling capacity and maintains stable DC-link voltage under any circumstances. [1] [12] [17] [21]

It could be concluded from the above discussion that Battery-Energy-Storage-Integrated DSTATCOM systems are capable of providing high performance during power quality improvement in hybrid renewable microgrids. [1] [4] [12]

2.4 LITERATURE ON BATTERY ENERGY STORAGE SYSTEMS (BESS)

The use of BESS is critical to modern renewable energy-based microgrids because they contribute positively to the reliability, stability, and power quality of the system. This is so because renewable energy sources, such as solar photovoltaic and wind energy systems, are characterized by fluctuations in voltage, frequency, and power balance. BESS plays a significant role in addressing these fluctuations by storing extra power during low demands and releasing power when there is generation deficiency or unexpected load variation. [4] [12] [16] [17] [21]

Many researchers have conducted different studies regarding the integration of battery storage systems into microgrid systems. In particular, Morstyn et al. proposed a model

predictive control algorithm applied to distributed microgrid battery energy storage systems to enhance power balancing and voltage regulation. Similarly, Zhuo evaluated some control methods for renewable energy microgrids coupled with battery storage, indicating the improved frequency stability and reduced power fluctuations. [12] [16] [21]

Several types of batteries like lithium-ion, lead-acid, nickel-cadmium, and sodium-sulfur batteries can be integrated into microgrid systems. Notably, the most commonly used type of batteries in microgrid systems is lithium-ion because of its higher energy density, long life cycles, faster charging capability, and low maintenance costs. For instance, Souza and Abdel-Rahman proposed a battery model for power system applications, emphasizing the significance of accurate state-of-charge (SOC) of the battery. [12]

Moreover, recent studies have involved BESS integrated with DSTATCOM in microgrid systems. Particularly, Mahela and Shaik designed an effective battery energy storage system integrated DSTATCOM to improve the harmonic compensation and voltage stability in distribution systems. Also, Wang et al. found out that energy storage assisted DSTATCOMs exhibit superior dynamic performance under sudden load changes and renewable intermittencies. [1] [3] [4] [21]

Intelligent battery management, adaptive control, and optimal methods have recently been proposed to ensure efficient energy storage system utilization within renewable energy microgrids. [12]

From the literature, it is clear that BESS is indispensable in ensuring reliable, sustainable, and efficient renewable energy microgrid systems. [4] [12] [16]

2.5 DSTATCOM CONTROL ALGORITHMS REPORTED IN LITERATURE

The efficiency of operation of a Distribution Static Compensator (DSTATCOM) depends on the efficiency of its control algorithm. Several control approaches have been introduced by researchers aiming at improved harmonics mitigation, reactive power compensation, voltage control, and dynamic response of distribution systems which are based on renewable energy sources. The above mentioned control algorithms are in charge of providing precise reference currents and controlling switching action of Voltage Source Converter (VSC). [1] [3] [16]

The most widely utilized control approach is known as the Synchronous Reference Frame (SRF) control method. It allows transforming three-phase currents into d-q components using Park transformation. As a result, harmonic and reactive components can be easily extracted. SRF control provides highly accurate compensation and rapid response to changing load situations. [3]

The other common control approach is the Instantaneous Reactive Power Theory (IRP) or p-q control method. IRP provides computation of instantaneous active and reactive components of power required for harmonic elimination and reactive power compensation. On the one hand, this approach is advantageous in terms of simple

implementation and fast transient response; on the other hand, p-q theory demonstrates unsatisfactory results when the input voltage is severely distorted. [3]

Hysteresis Current Control (HCC) is another widely applied control approach. HCC provides simple structure and fast switching. However, the compensation current in this case is controlled within the hysteresis band, and the switching frequency continuously changes.

In order to achieve better controller performance in nonlinear and dynamic operation conditions, it is possible to apply intelligent control techniques including FLC, ANN, and ANFIS control. FLCs do not require exact mathematical model of the system and can operate under nonlinear conditions efficiently. ANN and ANFIS provide high adaptability, compensation precision, and dynamic stability. [8] [21]

The current research is concentrated on applying adaptive and predictive control algorithms to BESS-integrated DSTATCOM systems. New algorithms improve the DC-link voltage regulation and reduce compensating current under nonlinear operating conditions. [1] [21]

Thus, it may be concluded that intelligent and adaptive algorithms increase the performance of DSTATCOM in hybrid microgrids powered by renewable energy sources. [1] [3] [12]

2.6 HYBRID RENEWABLE ENERGY MICROGRID STUDIES

In recent times, there has been much interest in hybrid renewable energy microgrids owing to rising energy demands, environmental protection and sustainable production of electrical energy. Renewable energy resources used in microgrids include PV power systems, wind energy conversion systems, fuel cells, and battery energy storage systems for ensuring uninterrupted power supply. Integrating various renewable energy sources increases the efficiency of these microgrids and reduces dependence on conventional power production from fossil fuels. [12] [16] [17]

The operational characteristics and control techniques in hybrid renewable microgrids have been studied by many researchers. Lasseter pioneered the concept of CERTS microgrid which showed feasibility of decentralized control for distributed energy resources. Researchers like Muñoz et al. conducted an analysis of performance and control of a photovoltaic-battery microgrid system. [12] [17]

There are two main operational modes for hybrid renewable microgrids namely, the grid connected operation and island operation. During the former state, surplus power generated through renewables is sold to the grid while latter state ensures operation during grid faults or disturbances in an independent manner. However, power generation through renewable energy is highly uncertain and unpredictable thereby posing problems like voltage fluctuation, frequency instability, harmonic distortion and reactive power imbalance. [3] [12] [16] [21]

Researchers have adopted different ways for overcoming the above mentioned problems using DSTATCOM, APFs, and UPQC. It has been seen that DSTATCOM coupled with battery energy storage systems (BESS) have resulted in higher transient stability, harmonic suppression, and voltage regulation during sudden changes in load conditions and uncertain renewable power. [1] [2] [3] [4] [19] [21]

The use of intelligent techniques for solving power quality problems in microgrids includes fuzzy logic controllers, artificial neural network (ANN)-based controllers, adaptive control, and model predictive control techniques. [4] [8] [12] [21]

From the available literature, it can be inferred that hybrid renewable energy microgrids with DSTATCOM integrated to BESS are a very good option for achieving reliable and stable power distribution in smart grids. [1] [12] [14] [16]

2.1 COMPARATIVE ANALYSIS OF EXISTING TECHNIQUES

Ref. No.	Author(s)	Technique / System	Controller Used	Compensation Capability	Renewable Source	Battery Integration	Limitations
[1]	Mahela and Shaik	BESS Integrated DSTATCOM	PI Controller	Harmonic mitigation, voltage regulation	Distribution system	Yes	Limited adaptive capability
[2]	Singh and Sharma	Four-leg VSC Based DSTATCOM	SRF Theory	Reactive power compensation and load balancing	Wind Energy System	No	Complex control implementation
[3]	Zaveri et al.	DSTATCOM for PQ Improvement	Hysteresis Control	Harmonic suppression	Utility Grid	No	Variable switching frequency
[4]	Razmi et al.	Distribution Network Compensation	Advanced Control Methods	Voltage stability and PQ improvement	Distributed Generation	No	High computational complexity
[5]	Nishanth and Saru Krishna	Hybrid Deep Learning DSTATCOM	Deep Learning Controller	Improved harmonic compensation	Smart Grid Renewable System	No	Requires training data
[6]	Wang et al.	Energy Storage Based	Adaptive Control	Dynamic voltage support	Renewable Microgrid	Yes	Battery management complexity

Ref. No.	Author(s)	Technique / System	Controller Used	Compensation Capability	Renewable Source	Battery Integration	Limitations
		DSTATCOM					
[7]	Morstyn et al.	Microgrid BESS System	Model Predictive Control	Power sharing and stability	Hybrid Microgrid	Yes	High computational burden
[8]	Zhuo	Renewable Microgrid Control	Adaptive Control	Frequency and voltage stabilization	Solar-Wind System	Yes	Complex controller tuning
[9]	Akdogan and Ahmed	Multi-Microgrid Compensation	Intelligent Controller	Unbalance compensation	Multi-Microgrid	Yes	Higher system cost
[10]	Wang et al.	Fuzzy Controlled DSTATCOM	Fuzzy Logic Controller	Reactive power support and THD reduction	Wind Energy System	No	Slower response under large disturbances
[11]	Sourav and Basu	ANFIS-Based DSTATCOM	ANFIS Controller	Harmonic elimination and voltage control	Renewable Energy System	No	Complex training process
[12]	Liu and Ghosh	Self-Charging DSTATCOM	Self-Charging Control	Voltage sag mitigation	Distribution Network	Yes	Limited energy capacity
[13]	Negi et al.	BESS for Reactive Power Support	Adaptive Controller	Reactive power compensation	Distribution Grid	Yes	Increased converter complexity
[14]	Khadkikar et al.	DSTATCOM for Distributed PV	SRF Controller	Voltage regulation and harmonic suppression	Solar PV	No	Reduced performance during severe disturbances
[15]	Mishra et al.	UPQC for Renewable Systems	Intelligent Control	Comprehensive PQ improvement	Renewable Energy System	Yes	High implementation cost

As shown by comparative analysis, Battery Energy Storage System based DSTATCOM offers better performance in comparison to other conventional compensation methods in terms of harmonics reduction, reactive power compensation, regulation of voltages, and transient stability. Furthermore, intelligent control methodologies like fuzzy, ANN, and ANFIS offer more adaptivity and dynamic response to compensate for the intermittent nature of renewable sources and nonlinear loads. Nevertheless, issues such as complexity of control system, battery handling, and computational efficiency are still significant topics in hybrid renewable microgrid applications. [1] [3] [8] [12] [16] [21]

2.7 RESEARCH GAPS IDENTIFIED

Though considerable amount of research work has been done till now related to improvement in power quality with the help of DSTATCOM in renewable energy integrated systems, yet some technical issues and knowledge gaps persist. The existing DSTATCOMs basically aim at compensating for reactive power and mitigating harmonics under steady state operations. But the conditions in case of renewable energy based microgrids are very dynamic due to solar and wind power generation. [1] [3] [4] [12] [16]

Most of the current studies use the conventional controllers like PID controllers, SRF theory and hysteresis current control method. All these algorithms offer satisfactory results in case of balanced loads, and under linear conditions. But in cases when the loading becomes nonlinear or unbalanced then the performance of all these algorithms becomes inferior. Moreover, conventional controllers take more time for achieving stability in case of transients. [16] [21]

Many researchers have proposed the utilization of intelligent control methods for improving the performance of DSTATCOM. These include fuzzy logic, ANN, ANFIS and adaptive controllers. The disadvantages of these algorithms include complex computations, difficult tuning and higher cost of implementation. Also, most of these studies are theoretical and based only on simulation analysis. [1] [8]

Yet another knowledge gap that persists among the current researchers related to DSTATCOM is the lack of integration with BESS for hybrid renewable microgrids. The current systems basically target only on the mitigation of harmonics and fail to coordinate the active/reactive power flow, DC link voltage and energy management. [1] [3] [12] [19]

Some recent researches related to DSC-PLL and VCO less PLL algorithm have revealed improvements in the area of harmonic compensation and fast convergence of the system. Nevertheless, very few studies have been made regarding integration of advanced PLL control strategy with battery incorporated DSTATCOM systems. [1] [3] [4] [9] [10] [12] [19]

Thus, there exists an urgent requirement of designing a superior DSTATCOM system integrated with battery and employing advanced control strategy which would offer better performance in terms of fast dynamics, improved harmonic compensation, effective voltage regulation and better stability in case of renewable based microgrids. [1] [3] [12] [16]

2.8 MOTIVATION FOR PROPOSED WORK

However, there are many power quality problems associated with the growing trend towards renewable energy-based microgrids. Renewable energy sources such as solar PV and wind energy plants are quite intermittent in nature and generate many disturbances like voltage fluctuation, harmonic distortion, reactive power imbalance and instabilities in power networks. Moreover, nonlinear load behavior in conjunction with power electronics also causes power quality degradation in the modern distribution systems. [3] [4] [12] [16] [17] [21]

Traditional compensating devices such as passive filters and capacitor banks cannot compensate in dynamic operating situations. Although the emergence of DSTATCOM as a custom power device for mitigation of harmonics and reactive power compensation, traditional DSTATCOM suffers from certain limitations concerning its transient response, DC-link voltage stabilization and capability of compensation under renewable energy fluctuation. [1] [3] [4] [16] [21]

However, recent studies have revealed that advanced control schemes such as DSC-PLL, SRF technique, fuzzy logic controllers, and ANN-based controller can enhance the performance of DSTATCOM systems. Out of these control techniques, DSC-PLL scheme has been found to perform well with regard to improved harmonic suppression, fast convergence, enhanced phase detection and low settling time when compared to the traditional PLL techniques. However, very few efforts have been made in the field of using advanced PLL technique along with BESS in DSTATCOM systems. [1] [3] [4] [8] [9] [10] [12]

It is well known that incorporation of battery energy storage system with DSTATCOM can increase the capacity of generating active power, enhance transient response, DC-link voltage regulation and improve overall system reliability in sudden changes in loads and renewable energy fluctuation. Hence, the main motivation behind this proposed work is to design an efficient Battery Energy Storage Integrated DSTATCOM system for superior performance and robust compensation. [1] [3] [12] [16] [21]

Thus, the present study focuses on designing an advanced DSTATCOM system for improving overall micro-grid performance while maintaining THD within permissible limits prescribed by IEEE standards. Top of Form [3] [4] [12]

CHAPTER 3

SYSTEM MODELING AND PROPOSED METHODOLOGY

3.1 PROPOSED HYBRID RENEWABLE MICROGRID ARCHITECTURE

The suggested architecture of the hybrid renewable microgrid comprises renewable energy generation systems, battery energy storage system (BESS), distribution static compensator (DSTATCOM), nonlinear loads, and utility grid connected through a point of common coupling (PCC). The aim of this system is to provide quality power, ensure voltage stability, minimize harmonic distortion, and increase the reliability of microgrid operation. [1] [3] [4] [12] [16] [21]

Within the suggested architecture, photovoltaic (PV) and wind generation units serve as the main sources of renewable energy. The mentioned renewable energy generation systems are connected to the distribution network using power electronics converters. However, since renewable energy sources exhibit highly variable characteristics, power fluctuations might result in voltage instability, reactive power mismatch, and harmonics creation. [3] [12] [16] [17] [21]

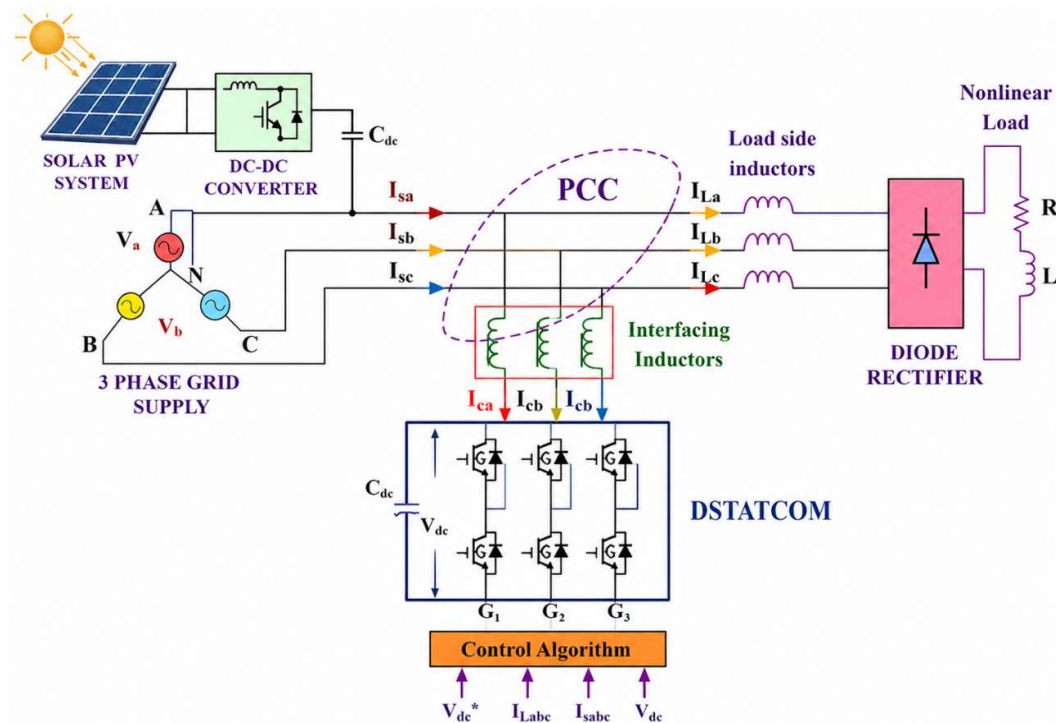


Fig.3.1 Proposed Battery Energy-Storage-Integrated DSTATCOM based Hybrid Renewable Microgrid [1] [12]

To resolve such issues, the Battery Energy Storage System is used along with the DSTATCOM. This is because the battery storage system stores excess energy whenever there are low loads or more production from renewable sources. Additionally, the battery provides support in case of renewable intermittencies and unexpected loading requirements. The BESS helps to regulate the DC link voltage and improve the transient stability. [1] [21]

The DSTATCOM system consists of a VSC operating as a source with IGBT devices, DC link capacitance, and control system. It is shunt connected to the Point of Common Coupling via interfacing inductor. DSTATCOM acts as a compensator providing compensating currents in order to reduce harmonic distortions, regulate terminal voltage, perform reactive power compensation, and control load current. [1] [3]

For the purpose of developing reference current components for power quality improvement, the suggested control strategy uses advanced extraction and synchronization methods. Moreover, the controller takes measurements of source voltages, load currents, and DC link voltage. [12]

A hybrid renewable microgrid has been designed to operate in grid connected and islanding modes. Whenever grid connection exists, it becomes possible to export excess renewable energy to the utility grid. However, in case of islanding, battery with DSTATCOM will provide stable voltage and frequency operation in the microgrid. [1] [12] [21]

Thus, it can be concluded that the developed design of the hybrid microgrid represents a feasible solution towards improved power quality and system stability.

3.2 MODELING OF SOLAR PV SYSTEM

- PV equivalent circuit
- I-V and P-V characteristics
- MPPT technique

Solar photovoltaic (PV) plants are among the most prevalent types of renewable energy sources employed in modern hybrid microgrids owing to the fact that they operate cleanly, require minimum maintenance, and solar energy is abundantly available. In the proposed hybrid renewable microgrid, the solar PV plant is a major source of distributed generation feeding power to the load and utility grids. However, the power output of a solar PV plant depends on various environmental factors like irradiance and temperature, thereby causing variation in voltages and currents. [12] [16] [17]

The working of a solar PV cell can be described as direct conversion of solar energy into electrical energy through the photovoltaic phenomenon. PV cells are arranged in series and parallel configurations to obtain a PV module and PV array to achieve the desired power and voltage ratings. The schematic representation of the PV cell consists of a current source, diode, series resistance, and shunt resistance. [17]

The output current of the PV cell can be expressed as:

$$I = I_{ph} - I_o \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V+IR_s}{R_{sh}} \quad (3.1)$$

where:

- I_{ph} = Photocurrent generated by solar irradiance
- I_o = Diode saturation current
- R_s = Series resistance
- R_{sh} = Shunt resistance
- q = Electron charge
- k = Boltzmann constant [8]
- T = Cell temperature
- n = Diode ideality factor

The I-V and P-V characteristics of the PV array depend on the variations in irradiance and temperature. An increase in solar irradiance results in an increase in the value of output current and output power whereas the increase in temperature causes the decrease in output voltage.

In order to maximize energy harvesting from the solar PV system, various techniques have been developed. Maximum Power Point Tracking (MPPT) technology is used in order to operate PV array at its optimum operating point for extracting maximum available power. Several MPPT algorithms are used for this purpose including Perturb and Observe (P&O) and Incremental conductance method. [1] [12]

In the given system architecture, the PV array is connected with the DC-Link through DC-DC boost converter. The output voltage is controlled by the boost converter and the power transfer takes place from PV system to DSTATCOM based micro-grid. [1] [12]

Therefore, the correct modeling of the solar PV system is required for renewable power generation analysis.

3.3 MODELING OF WIND ENERGY SYSTEM

The wind energy source is one of the most significant renewable energy sources used in hybrid microgrids because of its feasibility, environmental benefits, and ability to produce electrical energy without any fuel consumption. For the developed hybrid renewable microgrid, the wind energy conversion system (WECS) runs along with the solar photovoltaic system and Battery Energy Storage System (BESS) to ensure an uninterrupted and stable power generation for the connected loads. [12] [16] [17]

The wind energy conversion system includes components such as the wind turbine, gearbox, generator, power electronics converter, and control system. Here, wind turbine changes wind kinetic energy to mechanical energy that later converts into electrical energy using a generator. Power generated from the wind turbine is dependent on wind speed, air density, blade radius, and efficiency of the turbine.

The mechanical power extracted from the wind turbine can be expressed as:

$$P_m = \frac{1}{2} \rho A V^3 C_p \quad (3.2)$$

where:

- P_m = Mechanical power generated by the wind turbine
- ρ = Air density
- A = Swept area of turbine blades
- V = Wind velocity
- C_p = Power coefficient of the turbine

Power coefficient C_p shows the efficiency of the wind turbine that is dependent on the turbine design and tip speed ratio. As wind speed keeps varying continuously, the output power produced by the wind energy system is very much dynamic and unpredictable in nature.

In the present case, the wind turbine is mechanically coupled to a PMSG or Induction Generator through a coupling mechanism. AC power generated is changed to DC power through a rectifier and DC-link converters. Power electronics converters are needed to control the voltage, frequency, and power flow. [12]

In order to achieve maximum energy capture in the wind energy conversion system, Maximum Power Point Tracking (MPPT) control methods have been applied. In these methods, the generator speed and converters can be controlled with respect to the variation in wind speeds.

But because of the intermittent nature of the wind energy source, some voltage fluctuations, harmonics, and reactive power issues can take place in the microgrid. Thus, in order to mitigate them, Battery Energy Storage Integrated-DSTATCOM has been utilized. [1] [3] [12] [21]

Therefore, for the effective analysis of the performance of the system under consideration, proper modeling of the wind energy conversion system is very much important. [4] [12]

3.4 BATTERY ENERGY STORAGE SYSTEM MODELING

- Charging/discharging characteristics
- SOC equations
- Battery converter

The Battery Energy Storage System (BESS) is used in hybrid renewable microgrids for enhancing the reliability of the microgrid, voltage stability, power quality, and energy

management. The use of BESS in the proposed system is mainly for providing active power, maintaining stability of DC-link voltage, compensating intermittent renewable generation, and improving transient performance in case of any sudden load change or fault condition in the microgrid. [1] [4] [12] [16] [21]

The BESS is used to store extra energy supplied by renewable sources in low demand conditions and to provide energy when there is higher demand or insufficiency in generation from renewable sources. This is one of the unique characteristics of BESS that helps in maintaining the stability of the microgrid system. [12] [21]

In the proposed system, a Lithium-ion battery is used because of high energy density, long cycle life, fast charging process, and minimum maintenance of this type of battery. This battery system is connected with the DC-link of VSC using bidirectional DC-DC converter, which controls charging and discharging according to system needs and State of Charge (SOC).

The State of Charge (SOC) is the most important factor in designing a battery model. It is defined as the ratio of remaining battery capacity to the rated battery capacity and mathematically written as:

$$SOC = SOC_0 - \frac{1}{Q} \int i_b dt \quad (3.3)$$

where:

- SOC_0 = Initial state of charge
- Q = Battery capacity
- i_b = Battery current

The charging and discharging behavior of the battery depends upon the current, voltage at the terminals, temperature, and operating condition. During excess generation of renewables, the battery charges and draws power, but in case of lower generation or sudden load demand, the battery discharges and provides power.

Battery energy storage system converts the input voltage to the constant DC-link voltage of the DSTATCOM. This helps to improve the compensation ability, transient stability, and performance against harmonics of the system. [1] [3] [21]

The use of BESS along with DSTATCOM in the microgrid offers many benefits such as better voltage regulation, reactive power improvement, power fluctuation reduction, and efficient use of renewable energy sources. [1] [16]

It becomes imperative in the present scenario to model the battery energy storage system for effective energy management, transient analysis, and power quality improvement.

3.5 DSTATCOM CONFIGURATION AND OPERATION

A Distribution Static Compensator (DSTATCOM) is a custom power device that works by being connected in shunt and plays a major role in improving the quality of power in distribution networks and microgrids where renewable sources of energy have been utilized. The hybrid microgrid system that has been proposed involves the use of DSTATCOM alongside a battery energy storage system (BESS).

The proposed DSTATCOM mainly consists of the following components:

- Voltage Source Converter (VSC)
- DC-link capacitor
- Battery Energy Storage System
- Interfacing inductor
- Control unit
- Pulse Width Modulation (PWM) switching circuit

The DSTATCOM is connected in shunt configuration at the Point of Common Coupling (PCC) through interfacing inductors. The Voltage Source Converter is built using insulated gate bipolar transistor (IGBT) switches arranged in a three-phase bridge configuration. The VSC converts the DC power available from the battery and DC-link capacitor into controlled AC compensating voltage. [1]

The DC-link capacitor maintains a constant DC voltage required for converter operation. The Battery Energy Storage System connected across the DC-link provides additional active power support during sudden load changes and renewable energy fluctuations. This integration significantly improves the transient response and stability of the microgrid. [12] [16] [21]

The operation of DSTATCOM is based on the generation of compensating currents. The controller continuously senses source voltage, source current, load current, and DC-link voltage to determine the reference compensating current. Based on the reference signals, PWM pulses are generated to control the switching operation of the VSC. [1]

The compensating current injected by the DSTATCOM can be expressed as: [1]

$$I_c = I_L - I_s \quad (3.4)$$

where:

- = Compensating current injected by DSTATCOM [1]
- I_L = Load current
- I_s = Source current

When nonlinear loads generate harmonics and reactive power demand, the DSTATCOM injects equal and opposite compensating current into the system. As a result, the source current becomes nearly sinusoidal and in phase with the source voltage, thereby improving power factor and reducing Total Harmonic Distortion (THD). [1] [3]

During voltage sag or renewable intermittency conditions, the battery integrated DSTATCOM provides active power support and maintains DC-link voltage stability. Thus, the proposed DSTATCOM configuration effectively enhances overall power quality, system reliability, and microgrid stability under dynamic operating conditions. [1] [4] [12] [20] [21]

3.6 MATHEMATICAL MODELING OF DSTATCOM

The mathematical modeling of the Distribution Static Compensator (DSTATCOM) is essential for analyzing its dynamic behavior, compensation capability, and control performance in the proposed hybrid renewable microgrid. The DSTATCOM is modeled as a shunt connected Voltage Source Converter (VSC) interfaced with the distribution network through coupling inductors. The main objective of the DSTATCOM is to inject compensating current into the system for harmonic mitigation, reactive power compensation, voltage regulation, and load balancing. [1] [3] [12]

The three-phase source voltages of the system can be represented as:

$$v_a = V_m \sin(\omega t) \quad (3.5)$$

$$v_b = V_m \sin(\omega t - \frac{2\pi}{3}) \quad (3.6)$$

$$v_c = V_m \sin(\omega t + \frac{2\pi}{3}) \quad (3.7)$$

where:

- V_m = Maximum phase voltage
- ω = Angular frequency of the system

The source current contains both fundamental and harmonic components due to nonlinear loading. The DSTATCOM injects compensating current such that the source current remains sinusoidal and balanced. [1] [3]

The compensating current is mathematically expressed as:

$$i_c = i_L + i_s \quad (3.8)$$

where:

- i_c = Compensating current injected by DSTATCOM [1]
- i_L = Load current
- i_s = Source current

The dynamic equation of the interfacing inductor can be represented as:

$$L \frac{di_c}{dt} = v_s - v_c - Ri_c \quad (3.9)$$

where:

- L = Interfacing inductance
- R = Internal resistance
- v_s = Source voltage
- v_c = Converter output voltage

The DC-link capacitor voltage dynamics are given by:

$$C \frac{dv_{dc}}{dt} = I_{dc} - I_c \quad (3.10)$$

where:

- C = DC-link capacitance
- V_{dc} = DC-link voltage
- I_{dc} = DC-side current

For effective control, the three-phase quantities are transformed into d-q reference frame using Park transformation. The d-axis component controls active power exchange while the q-axis component controls reactive power compensation.

The DSTATCOM controller continuously regulates the DC-link voltage and generates reference compensating currents based on load and source conditions. Pulse Width Modulation (PWM) techniques are used for generating switching pulses to the IGBT-based Voltage Source Converter. [1]

Thus, the mathematical model of DSTATCOM provides the basis for designing control algorithms and analyzing system performance under various operating conditions in the proposed hybrid renewable microgrid. [1] [12]

3.7 CONTROL STRATEGY OF BATTERY-INTEGRATED DSTATCOM

The control strategy of the proposed Battery Energy-Storage-Integrated DSTATCOM is designed to achieve effective harmonic mitigation, reactive power compensation, voltage regulation, and stable operation of the hybrid renewable microgrid under dynamic operating conditions. The controller continuously monitors system parameters such as source voltage, load current, source current, and DC-link voltage to generate appropriate compensating signals for the Voltage Source Converter (VSC). [1] [3] [12]

The proposed control scheme mainly consists of the following stages:

- Reference current generation
- DC-link voltage control
- Harmonic compensation [3] [19]
- Reactive power compensation
- PWM pulse generation

The Battery Energy Storage System supports the DC-link during sudden load changes and renewable energy fluctuations. During excess renewable generation, the battery charges, whereas during low generation conditions it discharges to maintain stable operation. [16]

The generated reference currents are compared with actual source currents using hysteresis current control or PWM techniques to generate gating pulses for the IGBT switches of the VSC.

The proposed control strategy ensures:

- Fast dynamic response
- Harmonic suppression [3]
- Improved voltage regulation
- Reactive power compensation
- Stable DC-link voltage
- Enhanced transient stability [21]

Thus, the Battery-Integrated DSTATCOM control strategy significantly improves the power quality and operational reliability of the hybrid renewable microgrid under varying load and renewable energy conditions. [1] [4] [12] [16]

3.7.1 Reference Current Generation

Reference current generation is one of the most important stages in the control strategy of the proposed Battery Energy-Storage-Integrated DSTATCOM. The primary objective of this stage is to generate accurate compensating reference currents required for harmonic mitigation, reactive power compensation, load balancing, and voltage regulation in the hybrid renewable microgrid. [1] [3] [12]

In the proposed system, the source currents should remain balanced, sinusoidal, and in phase with the source voltages even under nonlinear and unbalanced loading conditions. To achieve this objective, the harmonic and reactive components of the load current are extracted using the Synchronous Reference Frame (SRF) theory. [3]

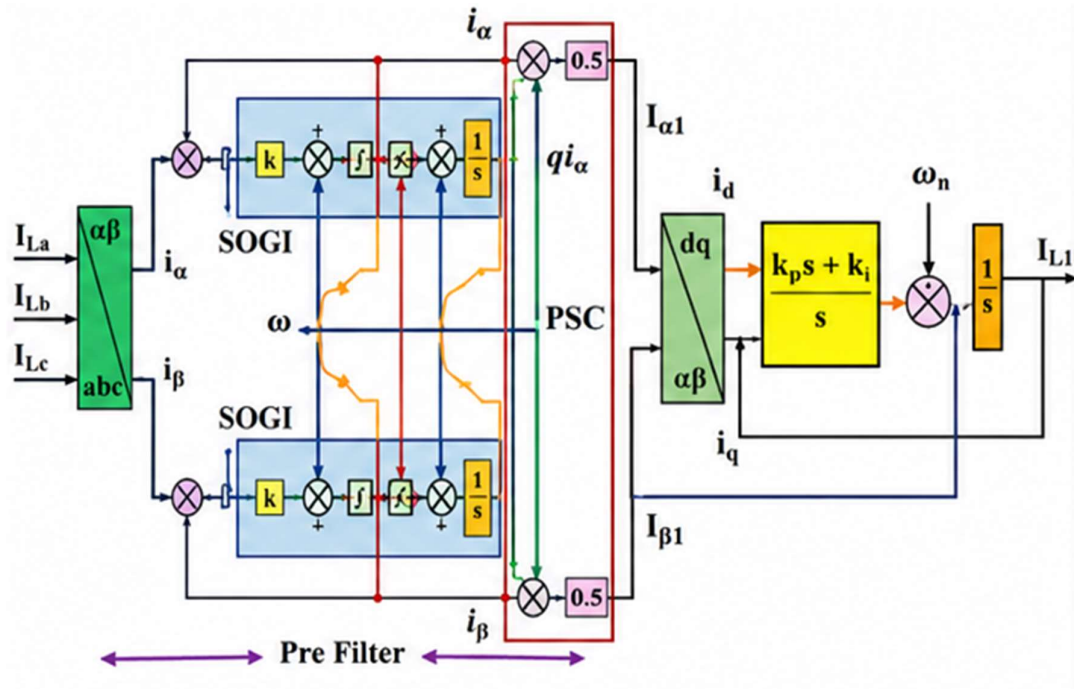


Fig. 3.3 SOGI based Reference Current Extraction Technique

Initially, the three-phase load currents (i_a, i_b, i_c) are transformed into d-q reference frame components using Park transformation. This transformation converts AC quantities into DC quantities, simplifying the control process and enabling accurate extraction of active and reactive current components.

The transformation equation is expressed as:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2\pi}{3} \right) & \cos \left(\theta + \frac{2\pi}{3} \right) \\ -\sin \theta & -\sin \left(\theta - \frac{2\pi}{3} \right) & -\sin \left(\theta + \frac{2\pi}{3} \right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (3.13)$$

In the d-q frame:

- i_d represents the active power component
- i_q represents the reactive power component

Low-pass filters are used to separate the fundamental components from harmonic components. The extracted harmonic and reactive current components are then used to generate the reference compensating currents required by the DSTATCOM. [1] [3]

The reference source current is calculated as:

$$i_s^* = i_L - i_c^* \quad (3.14)$$

where:

- i_s^* = Reference source current
- i_L = Load current
- i_c^* = Reference compensating current

The generated reference currents are compared with the actual source currents using hysteresis current control or PWM current control techniques to produce gating pulses for the Voltage Source Converter (VSC).

Accurate reference current generation ensures:

- Effective harmonic elimination [3]
- Reactive power compensation
- Balanced source current
- Improved power factor
- Reduced Total Harmonic Distortion (THD) [3]

Therefore, the reference current generation stage plays a vital role in enhancing the power quality and dynamic performance of the proposed Battery-Integrated DSTATCOM system. [1] [4]

3.7.2 DC-Link Voltage Control

DC-link voltage control plays a crucial role in the Battery Energy-Storage-Integrated DSTATCOM proposed. The main purpose of DC-link voltage control is to keep the DC-link voltage constant on the capacitor of Voltage Source Converter (VSC) under different operating conditions such as changing load and renewable energy. It is imperative for the stable working of the converter, harmonic compensation, and reactive power supply. [1] [3] [16] [19]

In the Battery Energy-Storage-Integrated DSTATCOM, DC-link capacitor acts as the source of stored energy, which either delivers or receives energy according to transient conditions. But due to switching losses and losses of converter along with the fluctuations in load, the DC-link voltage changes continuously. Thus, a proper control scheme is needed to control the voltage of DC-link to its desired value.

The DC-link voltage error is obtained by subtracting the reference DC-link voltage from the measured DC-link voltage:

$$V_{error} = V_{dc}^* - V_{dc} \quad (3.15)$$

where:

- V_{dc}^* = Reference DC-link voltage
- V_{dc} = Actual DC-link voltage

The voltage error signal is processed using a Proportional-Integral (PI) controller to generate the active power loss component required for maintaining DC-link voltage stability. The output of the PI controller is expressed as: [21]

$$I_{loss} = K_p V_{error} + K_i \int V_{error} dt \quad (3.16)$$

where:

- K_p = Proportional gain
- K_i = Integral gain
- I_{loss} = Loss component current

The generated loss component is added to the reference active current component for producing the final compensating reference current. The controller continuously adjusts converter switching to maintain constant DC-link voltage during dynamic operating conditions.

The Battery Energy Storage System (BESS) connected across the DC-link further improves voltage stability by supplying or absorbing active power during renewable intermittency and sudden load changes. During excess renewable generation, the battery charges and absorbs power, whereas during low generation conditions the battery discharges to support the DC-link voltage. [21]

Effective DC-link voltage regulation provides several advantages including:

- Improved converter stability [21]
- Faster transient response
- Enhanced harmonic compensation [3] [19]
- Better reactive power support
- Reduced voltage fluctuations
- Reliable operation under renewable energy variations [16]

Therefore, DC-link voltage control plays a crucial role in improving the dynamic performance and overall power quality of the proposed Battery-Integrated DSTATCOM system. [1] [4]

3.7.3 Harmonic Compensation Strategy

Harmonic compensation is one of the primary functions of the proposed Battery Energy-Storage-Integrated DSTATCOM system. In hybrid renewable microgrids, nonlinear loads such as rectifiers, power electronic converters, adjustable speed drives, and switching devices generate harmonic currents that distort the source current waveform. These harmonics degrade power quality, increase system losses, cause overheating of electrical equipment, and reduce overall system efficiency. [1] [3] [4] [12] [19]

The proposed DSTATCOM makes use of a high-end harmonic cancellation technique using SRF concept to remove harmonic components from the source current. The controller monitors the load current at all times and uses d-q transformation along with filters to isolate harmonic components from the current signal. [1] [3] [19]

First, the three-phase load currents undergo d-q transformation to transform them into rotating d-q coordinates. During this transformation, the fundamental frequency component gets represented in DC form while harmonic components get converted into AC form. Filters, namely low pass filters, are then used to remove harmonic components from the fundamental component. [3] [19]

Finally, compensating reference current signals are generated, followed by their conversion into the three-phase reference frame. The Voltage Source Converter feeds these compensating currents into the circuit to cancel out the harmonic currents caused by nonlinear loads. Consequently, the source current acquires sinusoidal nature, resulting in improved power quality and reduced harmonic distortion. [1] [3] [19] [21]

The compensating current required for harmonic mitigation is generated as: [3]

$$i_c^* = i_L - i_f \quad (3.17)$$

where:

- i_c^* = Reference compensating current
- i_L = Load current
- i_f = Fundamental source current component

The reference compensating current is generated and applied to the network via the Voltage Source Converter (VSC). The DSTATCOM generates the same magnitude but oppositely directed harmonic currents to compensate for the harmonics caused by the non-linear loads. Consequently, the source current remains balanced and nearly sinusoidal. [1] [3]

Either hysteresis current control or Pulse Width Modulation (PWM) algorithms can be utilized to generate switching pulses that control the operation of IGBT switches in the converter. This helps track the reference compensating currents accurately and ensures effective harmonic compensation. [1] [3] [19]

The Battery Energy Storage System (BESS) connected to the DC-link enhances the harmonic cancellation ability by stabilizing the DC-link voltage under dynamic loads and renewable energy fluctuations. As a result, the DSTATCOM maintains reliable compensation performance and improved power quality under varying operating conditions. [3] [16] [19]

The proposed harmonic compensation strategy provides several advantages including: [3] [19]

- Reduction in Total Harmonic Distortion (THD) [3]
- Improved source current waveform
- Better power factor
- Reduced heating losses
- Improved voltage stability [21]
- Compliance with IEEE-519 harmonic standards [3]

Simulation results show that the proposed Battery-Integrated DSTATCOM effectively reduces source current THD within permissible IEEE limits, thereby significantly improving overall power quality and microgrid performance. [1] [4] [12]

3.7.4 Reactive Power Compensation

Reactive power compensation is an important function of the proposed Battery Energy-Storage-Integrated DSTATCOM system for maintaining voltage stability and improving overall power quality in the hybrid renewable microgrid. Reactive power demand increases significantly due to inductive and nonlinear loads such as induction motors, transformers, converters, and industrial equipment. Excessive reactive power consumption leads to poor power factor, increased transmission losses, voltage fluctuations, and reduced system efficiency. [1] [4] [12] [21]

The proposed DSTATCOM operates as a shunt compensating device that injects or absorbs reactive power according to system requirements. The controller continuously monitors source voltage, load current, and reactive current components to generate appropriate compensating signals. By supplying the required reactive power locally at the Point of Common Coupling (PCC), the DSTATCOM reduces the reactive power burden on the utility source. [1]

Using Synchronous Reference Frame (SRF) theory, the reactive current component is extracted in the q-axis component of the d-q reference frame. The compensating reactive current is generated to eliminate the reactive component from the source current.

The reactive power compensation equation is expressed as:

$$Q = VI \sin \phi \quad (3.18)$$

where:

- **Q = Reactive power**
- **V = Source voltage**
- **I = Source current**
- **ϕ = Phase angle between voltage and current**

The compensating current injected by the DSTATCOM reduces the phase difference between source voltage and source current, thereby improving the power factor and maintaining balanced source currents. [1]

The Battery Energy Storage System (BESS) connected across the DC-link further enhances reactive power support capability during sudden load changes and renewable energy fluctuations. During transient conditions, the battery assists the DSTATCOM in maintaining stable DC-link voltage and effective compensation performance. [1] [16]

The proposed reactive power compensation strategy provides several advantages including:

- Improved power factor
- Reduced reactive power demand from utility grid
- Enhanced voltage regulation
- Reduced transmission losses
- Improved system efficiency
- Better transient stability [21]

Simulation results demonstrate that the proposed Battery-Integrated DSTATCOM effectively compensates reactive power under nonlinear and varying load conditions, resulting in improved voltage profile and stable microgrid operation. [1] [12]

3.8 PROPOSED CONTROL ALGORITHM

- Flowchart
- Control block diagram
- Switching logic

The proposed control algorithm for the Battery Energy-Storage-Integrated DSTATCOM is designed to achieve effective harmonic mitigation, reactive power compensation, voltage regulation, and improved dynamic stability in the hybrid renewable microgrid. The controller continuously monitors the electrical parameters of the system and generates suitable compensating signals for the Voltage Source Converter (VSC) under varying operating conditions. [1] [3] [12] [21]

The proposed control strategy is based on Synchronous Reference Frame (SRF) theory combined with DC-link voltage regulation and hysteresis current control techniques. The overall operation of the controller involves current sensing, reference current generation, harmonic extraction, reactive power compensation, and switching pulse generation for the DSTATCOM converter. [1] [3]

Initially, the three-phase source voltages and load currents are sensed at the Point of Common Coupling (PCC). The measured three-phase currents are transformed into d-q reference frame components using Park transformation. In the d-q frame, the active and reactive current components are separated for accurate compensation control.

Low-pass filters are used to extract the fundamental current components while eliminating harmonic components. The harmonic and reactive components are utilized to generate the reference compensating currents required by the DSTATCOM. [1] [3]

The DC-link voltage is continuously compared with the reference voltage value. The error signal is processed through a PI controller to generate the active power loss component required for maintaining stable DC-link voltage. The Battery Energy Storage System (BESS) connected across the DC-link assists in maintaining voltage stability during renewable intermittency and sudden load changes. [21]

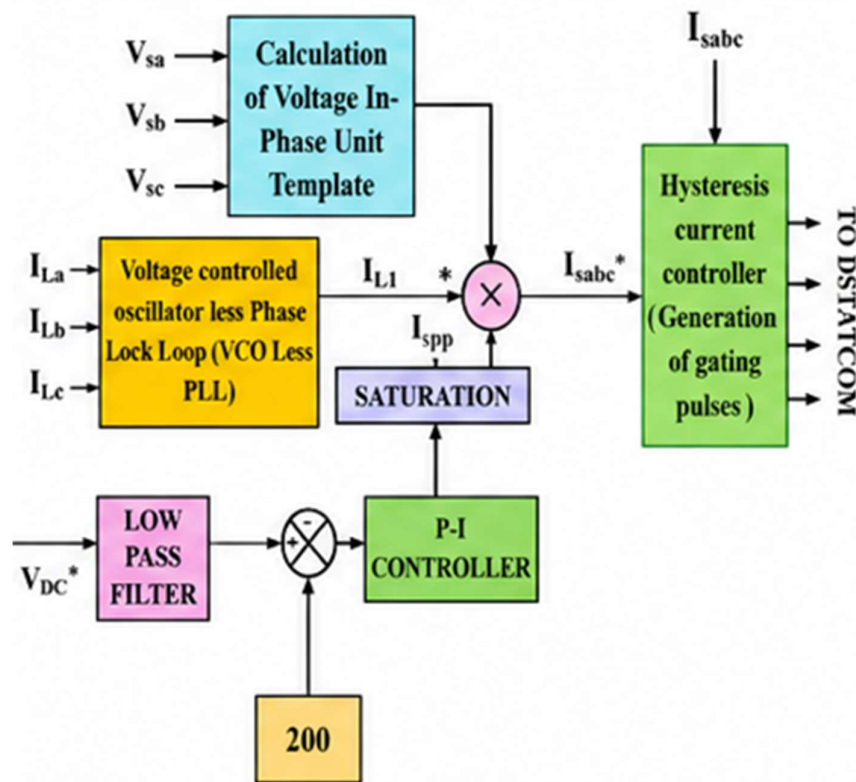


Fig. 3.4 Hysteresis Current Controller using VCO-Less PLL

The final reference current is obtained by combining the active power component and compensating current component. This reference current is compared with the actual source current using hysteresis current control. The hysteresis controller generates switching pulses for the IGBT switches of the Voltage Source Converter.

The proposed control algorithm offers several advantages including:

- Fast dynamic response
- Effective harmonic suppression [3]
- Improved reactive power compensation
- Stable DC-link voltage regulation
- Better transient stability [21]
- Reduced Total Harmonic Distortion (THD) [3]
- Improved source current quality

The overall control process of the proposed Battery-Integrated DSTATCOM can be summarized as follows:

1. Measurement of source voltage and load current
2. Transformation into d-q reference frame
3. Extraction of harmonic and reactive current components
4. DC-link voltage regulation using PI controller
5. Reference compensating current generation
6. PWM/Hysteresis switching pulse generation

7. Injection of compensating current into the system

Thus, the proposed control algorithm ensures stable and reliable operation of the hybrid renewable microgrid while significantly improving overall power quality performance. [4] [12]

3.9 MATLAB/SIMULINK IMPLEMENTATION

The proposed Battery Energy-Storage-Integrated DSTATCOM system is implemented and analyzed using MATLAB/Simulink environment with SimPowerSystems toolbox. MATLAB/Simulink provides an effective platform for modeling renewable energy systems, power electronic converters, battery storage systems, and advanced control algorithms under dynamic operating conditions. [1] [16]

The simulation model of the proposed hybrid renewable microgrid consists of the following major components:

- Solar Photovoltaic (PV) System [17]
- Wind Energy Conversion System
- Battery Energy Storage System (BESS)
- Voltage Source Converter (VSC) based DSTATCOM [1]
- Nonlinear Load
- Utility Grid
- Control System

The renewable energy sources are connected to the common DC-link through suitable power electronic converters. The Battery Energy Storage System is integrated across the DC-link to maintain voltage stability and support active power exchange during sudden load variations and renewable intermittency. [16] [21]

The DSTATCOM is modeled using a three-phase IGBT based Voltage Source Converter connected in shunt configuration at the Point of Common Coupling (PCC) through interfacing inductors. The control strategy is implemented using Synchronous Reference Frame (SRF) theory combined with PI controller and hysteresis current control techniques. [1]

The simulation process involves the following stages:

1. Measurement of source voltage and load current
2. Transformation of three-phase currents into d-q reference frame
3. Extraction of harmonic and reactive current components [3]
4. Generation of reference compensating current
5. DC-link voltage regulation using PI controller
6. PWM/Hysteresis pulse generation
7. Injection of compensating current through DSTATCOM [1]

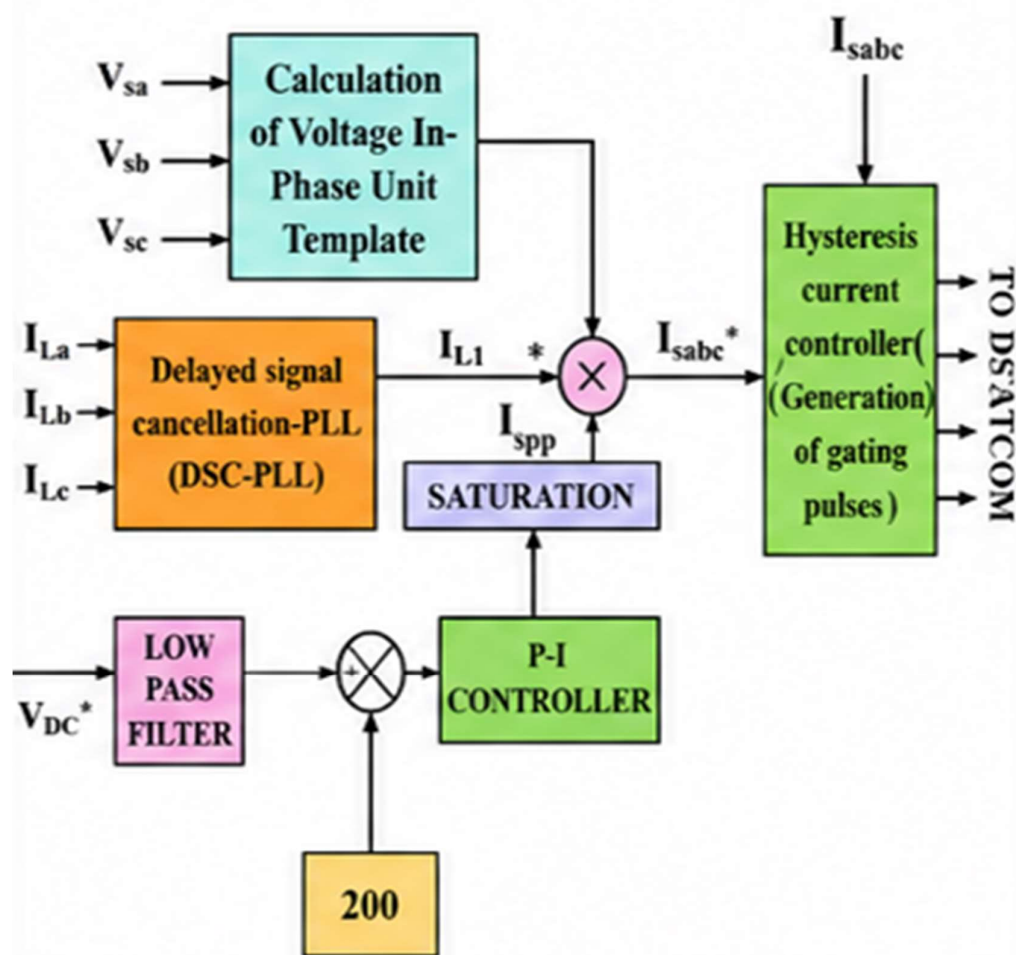


Fig. 3.5 DSC-PLL based DSTATCOM Control Structure

The Battery Energy Storage System is modeled using charging and discharging characteristics along with State of Charge (SOC) equations. The battery supports the DC-link voltage and improves transient stability during sudden disturbances and renewable fluctuations. [21]

Different operating conditions such as nonlinear loading, voltage sag, renewable intermittency, and sudden load changes are simulated to analyze the performance of the proposed system. Various electrical parameters including source voltage, source current, compensating current, reactive power, DC-link voltage, and Total Harmonic Distortion (THD) are observed and analyzed. [3] [20]

Harmonic distortion calculation is performed using FFT analysis software that is found in MATLAB/Simulink, which helps confirm that the system meets the requirements of IEEE-519 standards. It can be seen from the simulation results that the Battery-Integrated DSTATCOM system performs well in terms of reducing harmonics, improving voltage profile, compensating for reactive power, and improving power quality. [1] [3] [4] [12]

Hence, the MATLAB/Simulink implementation makes a good platform for confirming the performance of the system. It allows detailed analysis of system behavior under different operating conditions, including load variations, renewable energy fluctuations,

and transient disturbances. The simulation environment also helps in validating the effectiveness of the proposed control strategy before practical implementation. [1] [3] [16] [21]

3.10 SYSTEM PARAMETERS AND DESIGN SPECIFICATIONS

The performance of the proposed system depends on proper choice of system parameters and design criteria. The parameters used in the MATLAB/Simulink simulation are chosen according to conventional distribution system criteria and previous studies regarding DSTATCOM. These parameters will assure successful mitigation of harmonics, compensation of reactive power, voltage regulation, and stable operation of the hybrid renewable microgrid. [1] [3] [12]

The proposed system includes a three-phase distribution system that is integrated with a source of renewable energy along with battery energy storage, nonlinear load, and DSTATCOM at the Point of Common Coupling (PCC). The Voltage Source Converter is designed based on Insulated Gate Bipolar Transistor (IGBT) switches with proper DC-link voltage and interfacing inductance. [1] [16]

Appropriate selection of the DC-link capacitor, interfacing inductor, switching frequency, and controller gains is essential to achieve efficient converter performance and accurate compensation. The Battery Energy Storage System (BESS) is sized to provide sufficient active power support during renewable energy fluctuations and sudden load disturbances. These design considerations help maintain DC-link voltage stability, improve transient response, and enhance the overall reliability of the proposed system under dynamic operating conditions. [1] [3] [16] [21]

Table 3.1 System Parameters of Proposed Hybrid Renewable Microgrid

Parameter	Symbol	Value
Supply Voltage	(V _s)	415 V
System Frequency	(f)	50 Hz
Source Impedance	(Z _s)	0.01 Ω
DC-Link Voltage	(V _{dc})	700 V
DC-Link Capacitor	(C _{dc})	2200 μF
Interfacing Inductor	(L _f)	3 mH
Switching Frequency	(f _s)	10 kHz
Solar PV Rating	(P _{PV})	50 kW

Parameter	Symbol	Value
Wind System Rating	(P _w)	40 kW
Battery Voltage	(V _b)	400 V
Battery Capacity	(Q _b)	100 Ah
Nonlinear Load Rating	(P _L)	30 kW
Power Factor	PF	0.8 lagging

Design Specifications of DSTATCOM

The DSTATCOM is designed to compensate harmonic currents, maintain voltage stability, and improve source power factor under nonlinear loading conditions. The interfacing inductor is selected to limit current ripple and ensure smooth compensating current injection into the system. The DC-link capacitor is designed to maintain constant DC voltage during transient disturbances and converter switching operation. [1] [3] [21]

The Battery Energy Storage System connected across the DC-link improves active power support capability and enhances transient stability during renewable energy fluctuations. The PI controller gains are selected to achieve fast settling time, minimum overshoot, and stable DC-link voltage regulation. [16] [21]

The switching frequency of the PWM inverter is chosen to obtain better harmonic compensation and reduced Total Harmonic Distortion (THD). The proposed system is designed to maintain source current THD within IEEE-519 permissible limits. [3] [19]

The design objectives of the proposed system include:

- Reduction of source current harmonics [3]
- Reactive power compensation
- Voltage regulation improvement
- Fast transient response
- Stable DC-link voltage control
- Improved power factor
- Enhanced renewable energy utilization [16]

Therefore, proper selection of system parameters and converter specifications ensures reliable operation and improved power quality performance of the proposed Battery-Integrated DSTATCOM in the hybrid renewable microgrid. [1] [4] [12]

CHAPTER 4

SIMULATION RESULTS AND DISCUSSION

4.1 SIMULATION ENVIRONMENT

The proposed Battery Energy-Storage-Integrated DSTATCOM system for hybrid renewable microgrids is simulated using MATLAB/Simulink software environment with the SimPowerSystems toolbox. MATLAB/Simulink provides an efficient and flexible platform for modeling renewable energy systems, power electronic converters, battery storage systems, and advanced control algorithms under dynamic operating conditions. [1] [12] [16]

The simulation model consists of solar photovoltaic (PV) system, wind energy conversion system, Battery Energy Storage System (BESS), nonlinear load, utility grid, and a Voltage Source Converter (VSC) based DSTATCOM connected at the Point of Common Coupling (PCC). The renewable energy systems are integrated through power electronic converters, while the DSTATCOM is connected in shunt configuration for power quality enhancement. [1] [4] [16] [17]

The DSTATCOM is modeled using a three-phase IGBT based Voltage Source Converter with interfacing inductors and DC-link capacitor. The Battery Energy Storage System is connected across the DC-link to provide active power support and maintain DC-link voltage stability during renewable intermittency and sudden load disturbances. [1] [21]

The control algorithm of the proposed system is implemented using Synchronous Reference Frame (SRF) theory combined with PI controller and hysteresis current control techniques. The controller continuously monitors source voltage, source current, load current, and DC-link voltage for generating compensating reference currents.

The simulation is carried out under different operating conditions such as:

- Nonlinear loading conditions
- Voltage sag and swell conditions [20]
- Sudden load variation
- Renewable energy fluctuation [16]
- Harmonic disturbances [3]

FFT analysis tools available in MATLAB/Simulink are used to analyze harmonic distortion and Total Harmonic Distortion (THD) of the source current. The simulation results are evaluated in terms of voltage regulation, harmonic mitigation, reactive power compensation, transient response, and DC-link voltage stability. [3] [21]

The proposed system is designed to maintain THD within IEEE-519 permissible limits and improve overall power quality of the hybrid renewable microgrid. The simulation environment therefore provides a reliable platform for validating the effectiveness and dynamic performance of the proposed Battery Energy-Storage-Integrated DSTATCOM system. [1] [4] [12]

4.2 TEST CONDITIONS AND PERFORMANCE PARAMETERS

The performance of the proposed Battery Energy-Storage-Integrated DSTATCOM is evaluated under various operating conditions in the MATLAB/Simulink environment to analyze its effectiveness in improving power quality in the hybrid renewable microgrid. Different disturbances and loading conditions are applied to examine the dynamic response, harmonic compensation capability, reactive power support, and voltage regulation performance of the proposed system. [1] [3] [4] [12] [19]

The simulation study is carried out under both steady-state and transient operating conditions. Initially, the system performance is analyzed without DSTATCOM compensation to observe the effect of nonlinear loads and renewable energy fluctuations on the source current and voltage profile. Thereafter, the proposed Battery-Integrated DSTATCOM is connected at the Point of Common Coupling (PCC) to evaluate the improvement in system performance. [1] [16]

The following test conditions are considered in the simulation analysis:

- Nonlinear load operation
- Sudden load variation
- Voltage sag and swell conditions [20]
- Renewable energy intermittency [16]
- Reactive power imbalance
- Harmonic disturbances [3]
- Dynamic transient conditions

Nonlinear loads are connected to the distribution system to generate harmonic distortion and reactive power demand. Sudden load switching conditions are applied to analyze the transient stability and dynamic response of the DSTATCOM controller. Renewable energy fluctuations are introduced by varying solar irradiance and wind speed conditions. [1] [3] [16] [21]

The performance of the proposed system is evaluated using the following electrical and power quality parameters: [4]

4.1 Performance Parameters

Parameter	Description
Source Voltage	Voltage profile at PCC
Source Current	Compensated source current waveform
Load Current	Nonlinear load current characteristics
Compensating Current	Current injected by DSTATCOM
Reactive Power	Reactive power compensation capability
DC-Link Voltage	Stability of DC-link capacitor voltage

Parameter	Description
Power Factor	Improvement in source power factor
THD (%)	Total Harmonic Distortion of source current
Settling Time	Dynamic response of the controller
Voltage Regulation	Ability to maintain constant voltage

FFT analysis is performed to calculate Total Harmonic Distortion (THD) before and after compensation. The obtained THD values are compared with IEEE-519 standards to validate the effectiveness of the proposed control strategy. [3]

The simulation results are further compared for three operating cases:

1. Without compensation
2. Conventional DSTATCOM [1]
3. Proposed Battery-Integrated DSTATCOM [1]

The proposed system is expected to provide improved harmonic suppression, better reactive power compensation, stable DC-link voltage, faster transient response, and enhanced voltage regulation under varying operating conditions in the hybrid renewable microgrid. [3] [12]

4.3 PERFORMANCE WITHOUT DSTATCOM [1]

- Voltage profile
- Harmonic distortion [3]
- Power factor

The performance of the hybrid renewable microgrid without DSTATCOM compensation is analyzed to study the impact of nonlinear loads and renewable energy fluctuations on overall power quality. In this operating condition, the system is connected directly to nonlinear loads without any compensating device. As a result, significant harmonic distortion, reactive power demand, voltage fluctuation, and poor power factor are observed in the distribution system. [1] [3] [4] [12] [16]

Nonlinear loads such as diode rectifiers, power electronic converters, and adjustable speed drives draw distorted current from the source. These distorted currents contain harmonic components that degrade the quality of source current and voltage waveforms. Due to the absence of a compensating device, the source must supply both active and reactive power demanded by the load, resulting in increased transmission losses and poor system efficiency. [3]

The source current waveform under uncompensated conditions becomes highly distorted and unbalanced. The Total Harmonic Distortion (THD) of the source current increases

significantly beyond IEEE-519 permissible limits. FFT analysis of the source current indicates the presence of higher-order harmonics generated by nonlinear loading conditions. [3]

The voltage profile at the Point of Common Coupling (PCC) also experiences fluctuations due to reactive power imbalance and renewable energy intermittency. During sudden load variation and renewable power fluctuation, voltage sag and transient disturbances are observed in the system. [16] [20]

The following observations are obtained under uncompensated operating conditions:

- Distorted source current waveform
- High Total Harmonic Distortion (THD) [3]
- Poor power factor
- Increased reactive power demand
- Voltage fluctuation at PCC
- Reduced system stability [21]
- Higher transmission losses

Table 4.2 Performance Without DSTATCOM

Parameter	Observed Value
Source Current THD	High (>20%)
Power Factor	Low (0.75–0.80 lagging)
Voltage Regulation	Poor
Reactive Power Demand	High
Source Current Quality	Distorted
System Stability	Reduced

The absence of DSTATCOM compensation leads to deterioration in overall power quality and system reliability. The source current contains significant harmonic components and becomes non-sinusoidal due to nonlinear loading conditions. [1] [3] [4]

Therefore, an advanced compensation device such as Battery Energy-Storage-Integrated DSTATCOM is required to mitigate harmonics, compensate reactive power, regulate voltage, and improve the overall performance of the hybrid renewable microgrid. [1] [3] [12]

4.4 PERFORMANCE WITH CONVENTIONAL DSTATCOM

The performance of the hybrid renewable microgrid with conventional DSTATCOM is analyzed to evaluate the improvement in power quality compared to the uncompensated system. In this case, a conventional Voltage Source Converter (VSC) based DSTATCOM is connected in shunt configuration at the Point of Common Coupling (PCC) without Battery Energy Storage System (BESS) integration. [1] [4] [12]

The conventional DSTATCOM injects compensating current into the system to suppress harmonic components and compensate reactive power demanded by nonlinear loads. The controller continuously senses source current and load current to generate reference compensating signals using Synchronous Reference Frame (SRF) theory and PWM switching techniques. [1] [3]

After connecting the DSTATCOM, the source current waveform becomes more balanced and sinusoidal compared to the uncompensated condition. The compensating current injected by the DSTATCOM effectively reduces harmonic distortion and improves source current quality. Reactive power demand from the utility source is also reduced significantly due to local reactive power support provided by the compensator. [1] [3]

The FFT analysis of source current indicates substantial reduction in Total Harmonic Distortion (THD). The THD value decreases within acceptable limits and approaches IEEE-519 standards. The source power factor also improves because the source current becomes nearly in phase with the source voltage. [3]

The DC-link capacitor of the DSTATCOM maintains converter operation during compensation. However, due to the absence of Battery Energy Storage System support, fluctuations in DC-link voltage may occur during sudden load variation and renewable energy intermittency. The transient response of the conventional DSTATCOM is moderate under dynamic operating conditions. [1] [16]

The following improvements are observed after connecting the conventional DSTATCOM:

- Reduction in source current harmonics [3]
- Improved source current waveform
- Better reactive power compensation
- Improved power factor
- Reduced voltage fluctuations
- Enhanced voltage regulation

Table 4.3 Performance with Conventional DSTATCOM

Parameter	Observed Performance
Source Current THD	Reduced ($\approx 4-8\%$)
Power Factor	Improved (≈ 0.95)

Parameter	Observed Performance
Voltage Regulation	Improved
Reactive Power Demand	Reduced
Source Current Quality	Nearly sinusoidal
Dynamic Response	Moderate

Although the conventional DSTATCOM significantly improves system performance, it still faces limitations under renewable intermittency and sudden load disturbances due to lack of active power support. The DC-link voltage regulation capability and transient stability are comparatively lower than Battery-Integrated DSTATCOM systems. [1] [21]

Therefore, integration of Battery Energy Storage System with DSTATCOM is proposed to further enhance power quality, transient stability, and compensation capability in hybrid renewable microgrids. [1] [4] [12] [21]

4.5 PERFORMANCE WITH BATTERY-INTEGRATED DSTATCOM

The performance of the proposed Battery Energy-Storage-Integrated DSTATCOM is analyzed under various operating conditions to evaluate its effectiveness in improving power quality and enhancing system stability in the hybrid renewable microgrid. In this configuration, the Battery Energy Storage System (BESS) is connected across the DC-link of the DSTATCOM to provide active power support, maintain DC-link voltage stability, and improve transient response during renewable energy fluctuations and sudden load variations. [1] [4] [12] [16] [21]

This proposed system works by adding a compensating current into the network to mitigate harmonics, reactive power compensation, voltage regulation, and balancing of source currents. The inclusion of the battery system enhances the dynamics of the DSTATCOM compared to the traditional setup. [1] [3]

The proposed Battery-Integrated DSTATCOM successfully attenuates harmonic distortion in the source current when nonlinear loads are presented. The waveform of the source current approaches near sinusoidal and balanced operation. The FFT analysis shows that there is reduction in THD in accordance to IEEE-519 standards. [1] [3]

In the case of sudden change in load or intermittent operation of the renewable energy source, the battery system maintains the DC link voltage. In case of surplus renewable power generation, the battery charges while for insufficient renewable power, the battery discharges. This active power support helps maintain energy balance within the system and improves the overall stability of the microgrid. [21]

The proposed control method based on SRF theory and PI controller offers fast response and accurate compensating current generation. There is an improvement in the settling time and PCC voltage variation reduction. As a result, the system demonstrates enhanced transient performance, improved voltage regulation, and reliable operation under dynamic operating conditions. [1] [3] [21]

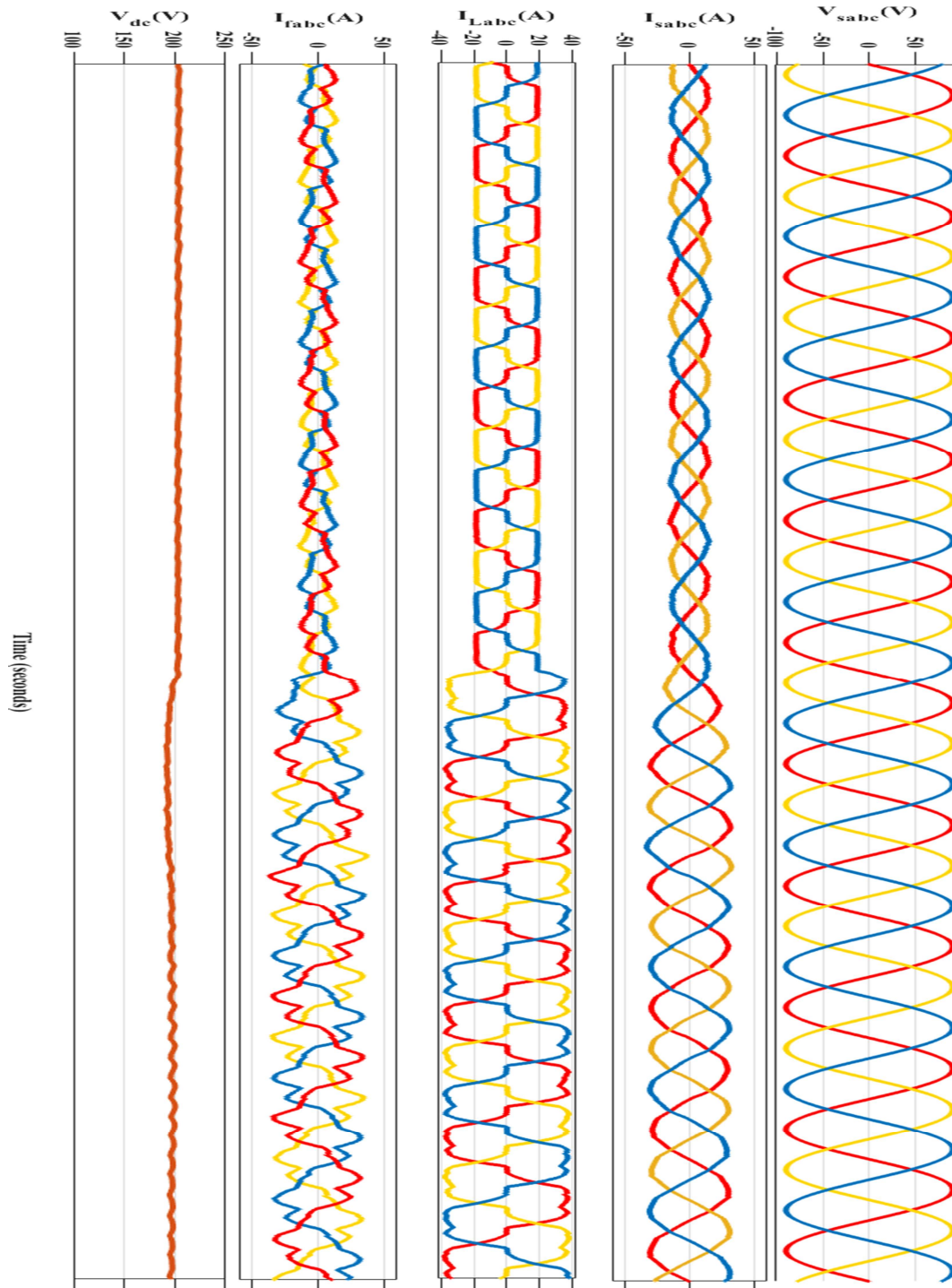


Fig. 4.1 FFT Analysis of Source Current after Compensation

The following improvements are observed with the proposed Battery-Integrated DSTATCOM:

- Significant reduction in harmonic distortion [3]
- Improved reactive power compensation
- Stable DC-link voltage regulation
- Enhanced transient stability [21]
- Better voltage profile at PCC
- Improved source power factor
- Fast dynamic response during disturbances
- Effective compensation under renewable intermittency

Table 4.4 Performance with Battery-Integrated DSTATCOM [1]

Parameter	Observed Performance
Source Current THD	Reduced (<5%)
Power Factor	Improved (≈ 0.99)
Voltage Regulation	Excellent
Reactive Power Demand	Highly Reduced
Source Current Quality	Balanced and sinusoidal
Dynamic Response	Fast
DC-Link Voltage Stability	Highly Stable
System Reliability	Improved

The simulation results demonstrate that the proposed Battery Energy-Storage-Integrated DSTATCOM provides superior performance compared to conventional DSTATCOM systems. The integration of BESS improves compensation capability, maintains stable operation during dynamic conditions, and significantly enhances overall power quality in the hybrid renewable microgrid. [1] [4] [12]

4.6 HARMONIC ANALYSIS

Harmonic analysis is conducted to determine the capability of the proposed BES-DSTATCOM for reducing harmonic distortion that occurs as a result of nonlinear loads in the microgrid. Harmonic generation happens because of power electronic converter, rectifier, adjustable speed drives, and switching device connections within the distribution system. They produce harmonics that distort the source current, lead to higher losses, decrease overall system efficiency, and hamper the proper functioning of electrical machinery. [1] [3] [12]

The process of harmonic compensation in the proposed system is done by using the DSTATCOM control strategy using Synchronous Reference Frame (SRF) and PWM Switching technique. In the process of compensation, compensating current is produced, which cancels out the unwanted harmonic currents in the nonlinear load. As a result, the source current is improved in terms of Total Harmonic Distortion (THD). [1] [3] [19]

For analyzing the harmonic contents before and after the compensation process, FFT analysis is carried out in MATLAB/Simulink. The FFT plot of the uncompensated source current shows noticeable lower-order and higher-order harmonic components, indicating poor power quality. After the Battery-Integrated DSTATCOM is connected, these harmonic components are significantly reduced, and the source current waveform becomes nearly sinusoidal. [1] [3]

As per the FFT analysis of the compensated source current, the THD value is estimated to be around 2.95%, which complies with IEEE-519 standard. This substantial reduction in THD confirms the effectiveness of the proposed compensation method and demonstrates its ability to improve the overall power quality of the hybrid renewable microgrid. [3] [21]

THD Analysis Result

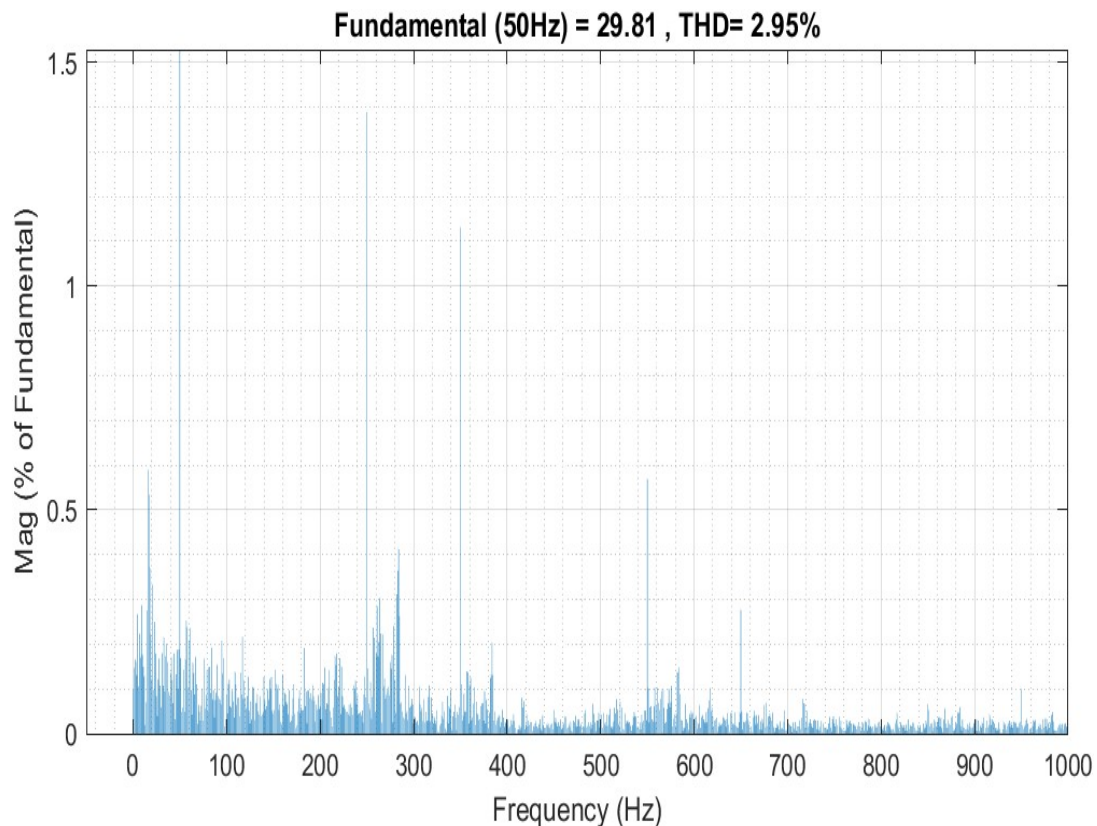


FIG 4.2 Performance Waveforms of Proposed Battery Energy-Storage-Integrated DSTATCOM

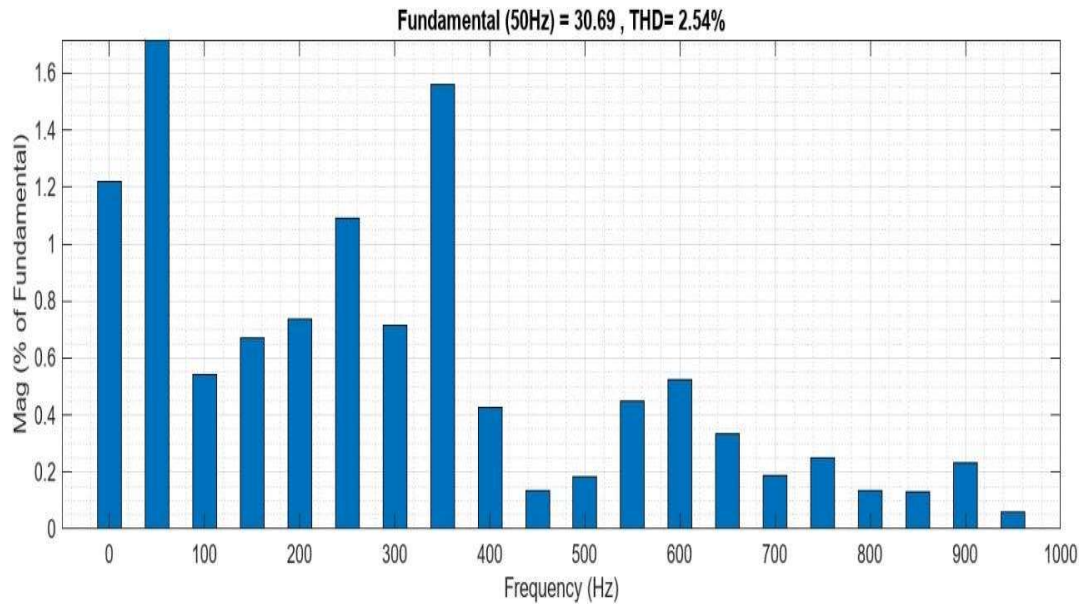


Fig. 4.3 FFT Analysis of Source Current after Compensation

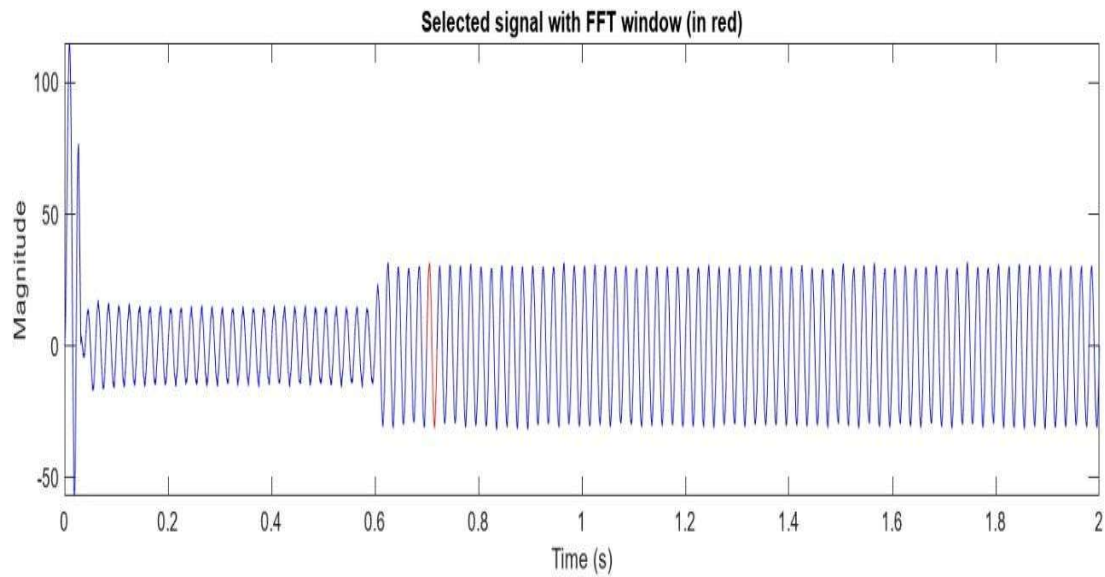


Fig. 4.4 Harmonic Spectrum of Source Current Using Proposed BESS-DSTATCOM

- Compliance with IEEE-519 standards
- Enhanced overall power quality [4]

Therefore, the proposed Battery-Integrated DSTATCOM effectively mitigates harmonics and ensures stable and reliable operation of the hybrid renewable microgrid under nonlinear loading conditions. [1] [3] [12]

4.7 REACTIVE POWER COMPENSATION ANALYSIS

Reactive power compensation analysis is carried out to evaluate the capability of the proposed Battery Energy-Storage-Integrated DSTATCOM in improving power factor, reducing reactive power demand, and maintaining voltage stability in the hybrid renewable microgrid. Nonlinear and inductive loads connected to the distribution system consume large amounts of reactive power, which results in poor power factor, increased line losses, voltage fluctuations, and reduced system efficiency. [1] [12] [21]

For the uncompensated case, the utility source delivers both real and reactive power to the load. As a result, there is a considerable phase difference between source voltage and source current resulting in low power factor and unstable voltage profile at PCC.

The proposed DSTATCOM functions as a shunt type compensating device that feeds compensating reactive current to the power system as per the load requirement. The controller constantly senses the source voltage and current to provide appropriate compensating currents based on SRF theory. The compensating current injected reduces the reactive component in source current, thus improving the power factor and voltage profile. [1]

Also, the BESS connected between the DC-links aids in achieving better compensation even when there are sudden load changes and renewables power variations. The battery allows active power flow and maintains constant DC link voltage, thereby increasing the efficiency of converter operation and enhancing transient performance. [16] [21]

The simulation results reveal that once the proposed Battery-integrated DSTATCOM is implemented, source current gets synchronized with the source voltage. As a result, the amount of reactive power delivered by the utility grid reduces considerably, while the power factor approaches unity. This demonstrates the effectiveness of the proposed system in reactive power compensation and power quality enhancement. [1] [3] [21]

Table 4.6 Reactive Power Compensation Analysis

Operating Condition	Reactive Power Demand	Power Factor
Without Compensation	High	0.75 – 0.80 lagging
Conventional DSTATCOM	Reduced	≈ 0.95
Proposed BESS-DSTATCOM	Highly Reduced	≈ 0.99

The proposed system provides the following improvements:

- Effective reactive power compensation
- Improved power factor close to unity
- Reduced burden on utility source
- Enhanced voltage stability [21]
- Reduced transmission losses
- Improved overall system efficiency

The dynamic response of the proposed system during sudden load variation demonstrates that the Battery-Integrated DSTATCOM rapidly compensates reactive power demand and restores stable operating conditions. The integration of battery storage significantly enhances compensation performance under renewable intermittency and transient disturbances. [1]

Therefore, the proposed Battery Energy-Storage-Integrated DSTATCOM effectively improves reactive power compensation capability and ensures stable operation of the hybrid renewable microgrid under varying operating conditions. [1] [12]

4.8 VOLTAGE REGULATION PERFORMANCE

Reactive power compensation analysis is carried out to evaluate the capability of the proposed Battery Energy-Storage-Integrated DSTATCOM in improving power factor, reducing reactive power demand, and maintaining voltage stability in the hybrid renewable microgrid. Nonlinear and inductive loads connected to the distribution system consume large amounts of reactive power, which results in poor power factor, increased line losses, voltage fluctuations, and reduced system efficiency. [1] [12] [21]

In the uncompensated condition, the utility source supplies both active and reactive power demanded by the load. This causes a significant phase difference between source voltage and source current, leading to poor power factor and unstable voltage profile at the Point of Common Coupling (PCC).

The proposed DSTATCOM operates as a shunt compensating device and injects reactive compensating current into the system according to load requirements. The controller continuously monitors source voltage and current signals to generate appropriate compensating reference currents using Synchronous Reference Frame (SRF) theory. The injected compensating current minimizes the reactive component of the source current, thereby improving the power factor and voltage profile. [1]

The Battery Energy Storage System (BESS) connected across the DC-link further enhances compensation capability during sudden load changes and renewable energy fluctuations. The battery supports active power exchange and maintains stable DC-link voltage, which improves overall converter performance and transient stability. [16] [21]

Simulation results show that after connecting the proposed Battery-Integrated DSTATCOM, the source current becomes nearly in phase with the source voltage.

Consequently, the reactive power supplied by the utility grid decreases significantly and the power factor improves close to unity. [1]

Table 4.7 Reactive Power Compensation Analysis

Operating Condition	Reactive Power Demand	Power Factor
Without Compensation	High	0.75 – 0.80 lagging
Conventional DSTATCOM	Reduced	≈ 0.95
Proposed BESS-DSTATCOM	Highly Reduced	≈ 0.99

The proposed system provides the following improvements:

- Effective reactive power compensation
- Improved power factor close to unity
- Reduced burden on utility source
- Enhanced voltage stability [21]
- Reduced transmission losses
- Improved overall system efficiency

The dynamic response of the proposed system during sudden load variation demonstrates that the Battery-Integrated DSTATCOM rapidly compensates reactive power demand and restores stable operating conditions. The integration of battery storage significantly enhances compensation performance under renewable intermittency and transient disturbances. [1]

Therefore, the proposed Battery Energy-Storage-Integrated DSTATCOM effectively improves reactive power compensation capability and ensures stable operation of the hybrid renewable microgrid under varying operating conditions. [1] [12]

4.9 BATTERY CHARGING AND DISCHARGING CHARACTERISTICS

The charging and discharging characteristics of the Battery Energy Storage System (BESS) are analyzed to evaluate its role in maintaining stable operation of the proposed hybrid renewable microgrid. The Battery Energy Storage System integrated with the DSTATCOM provides active power support, stabilizes the DC-link voltage, and enhances transient performance during renewable energy fluctuations and sudden load variations. [1] [12] [16]

In the proposed system, the battery operates in both charging and discharging modes depending on renewable power generation and load demand conditions. During periods of excess renewable energy generation, such as high solar irradiance or increased wind speed, the generated power exceeds load demand. Under this condition, the surplus

energy is stored in the battery through the bidirectional DC-DC converter, and the battery operates in charging mode. [16]

Conversely, during low renewable generation or sudden increase in load demand, the battery discharges stored energy to support the microgrid and maintain stable operation. The discharging operation assists the DSTATCOM in maintaining constant DC-link voltage and compensating transient power imbalance within the system. [1] [12]

The charging and discharging process of the battery is controlled based on the State of Charge (SOC) and DC-link voltage conditions. The SOC continuously varies according to battery current and operating duration.

The SOC equation is given by:

$$SOC = SOC_0 - \frac{1}{Q} \int i_b dt \quad (4.1)$$

where:

- SOC = Initial state of charge
- SOC_0 = Rated battery capacity
- i_b = Battery current

Simulation results show that the battery charges during excess renewable generation and discharges during sudden disturbances or renewable intermittency. The Battery Energy Storage System effectively stabilizes the DC-link voltage and improves compensation performance of the DSTATCOM during dynamic operating conditions. [1]

Table 4.8 Battery Charging and Discharging Characteristics

Operating Condition	Battery Mode	System Effect
Excess Renewable Generation	Charging	Stores surplus energy
Low Renewable Generation	Discharging	Supplies active power
Sudden Load Increase	Discharging	Supports DC-link voltage
Light Load Condition	Charging	Maintains energy reserve

The following improvements are achieved due to battery integration:

- Stable DC-link voltage regulation
- Improved transient stability [21]
- Better renewable energy utilization [16]
- Reduced voltage fluctuations
- Enhanced compensation capability
- Improved system reliability

The integration of Battery Energy Storage System significantly enhances the dynamic performance of the DSTATCOM and ensures reliable operation of the hybrid renewable microgrid under varying operating conditions. Therefore, proper charging and discharging control of the battery system plays a crucial role in achieving efficient energy management and improved power quality performance. [1] [4] [12]

4.10 DYNAMIC RESPONSE UNDER DISTURBANCES

- Sudden load variation
- Renewable intermittency
- Fault conditions

Transient behavior analysis for the proposed Battery-Integrated DSTATCOM design has been done to analyze its capability to compensate different types of disturbances for the stability of the power system and improve its power quality. There are numerous disturbances that occur frequently in practical applications like load disturbance, renewable intermittency, voltage sag, and faults which hamper the stability of the power system. [1] [4] [12] [16] [20] [21]

In order to counter these disturbances, the proposed Battery Energy-Storage-Integrated DSTATCOM works effectively to provide fast dynamic response and keep the system running smoothly.

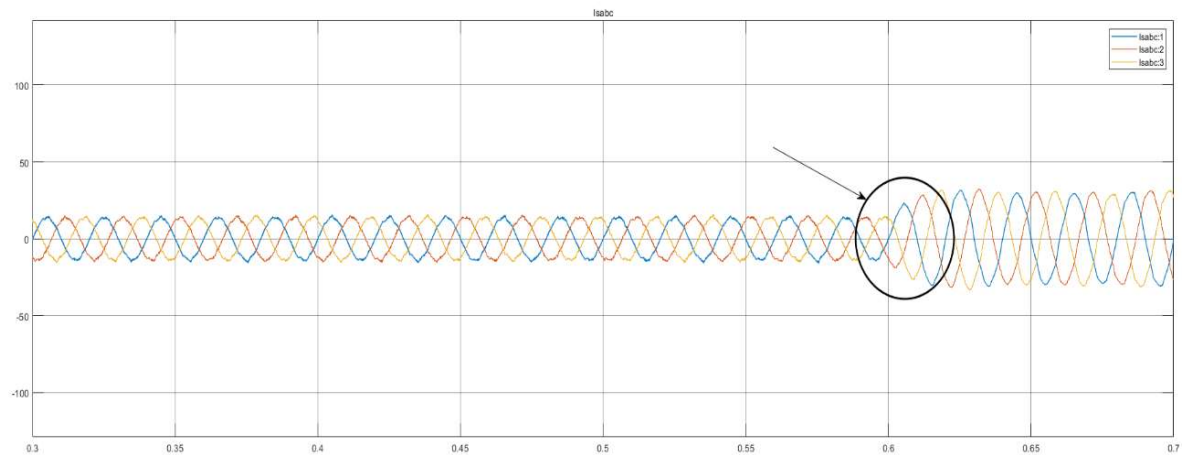


Fig. 4.6 Source Current Waveforms during Load Disturbance and Compensation

4.10.1 Response Under Sudden Load Variation

Sudden load variations may cause a change in source currents, reactive power demand, and voltage profile. Without any control, the source current will be distorted and power factor will be degraded.

With the introduction of proposed Battery-Integrated DSTATCOM in the system, the control module quickly responds to these disturbances by generating compensating

currents. Active power support during sudden increase in load and maintaining constant DC-link voltage is provided by Battery Energy Storage System. [1]

Results from simulation indicate that the source current becomes balanced and sinusoidal with least settling time during load variation.

4.10.2 Response Under Renewable Intermittency

Solar PV system and wind turbines produce electricity intermittently. Due to intermittent production of power in the microgrid, the system is exposed to voltage instability and frequency disturbance. [12] [16] [21]

By switching between charging and discharging modes based on the requirement, the proposed Battery Energy Storage System helps in compensating for these disturbances. During low renewable generation, the battery acts as an active power generator while excess energy is stored in the battery. [1]

This proposed DSTATCOM keeps PCC voltage stable during renewable intermittency. [21]

4.10.3 Response Under Fault Conditions

Voltage sag occurs due to fault in the distribution system. Voltage sag leads to high transient current and system instability. The control module of the proposed DSTATCOM quickly reacts to faults by injecting compensating current. [1] [20] [21]

Due to active power support from battery-integrated DC-link, voltage recovery takes place faster without producing any unwanted oscillations.

Table 4.9 Dynamic Response Analysis Under Disturbances

Disturbance Condition	System Response Without Compensation	Proposed BESS-DSTATCOM Response
Sudden Load Variation	High current distortion and voltage fluctuation	Fast stabilization and harmonic suppression
Renewable Intermittency	Voltage instability and poor power quality	Stable voltage and improved compensation
Fault Condition	Severe voltage sag and transient oscillation	Rapid voltage recovery and stable operation

The proposed Battery Energy-Storage-Integrated DSTATCOM demonstrates the following dynamic performance improvements:

- Fast transient response
- Reduced settling time
- Stable DC-link voltage
- Improved voltage recovery
- Effective harmonic suppression
- Enhanced transient stability
- Reliable operation under varying disturbances

Therefore, simulation results confirm that the proposed Battery-Integrated DSTATCOM provides excellent dynamic response and significantly enhances the stability and power quality of the hybrid renewable microgrid under disturbed operating conditions. [1] [4] [12] [21]

4.11 COMPARATIVE PERFORMANCE ANALYSIS

In order to compare the performance of proposed Battery-Integrated DSTATCOM with that of uncompensated distribution system as well as conventional DSTATCOM system, a comparative performance analysis is performed based on some of the most crucial power quality metrics such as Total Harmonic Distortion (THD), reactive power compensation, voltage regulation, power factor improvement, transient performance and DC-link voltage control. [1] [3] [4] [21]

The uncompensated distribution system suffers from relatively low power quality performance due to non-linear loads and intermittent nature of renewable energy sources. High harmonic distortion, high reactive power requirement, voltage fluctuation and poor power factor are some of the main problems faced by the system. In addition, source current becomes highly distorted and system suffers from instability when encountering with transients. [3] [4] [16]

Conventional DSTATCOM can help compensate harmonics and reactive power in the system by injecting compensating current. As a result, the waveform of source current tends to be nearly sinusoidal and voltage regulation performance improves to some level. But lack of Battery Energy Storage System (BESS) makes the transient performance and DC-link voltage control capability weak in the system. [1] [3] [19] [21]

Battery-Integrated DSTATCOM offers better performance than uncompensated and conventional DSTATCOM distribution systems. By integrating BESS, the performance of active power support, DC-link voltage regulation, transient performance and stability can be significantly enhanced. Simulation results confirm substantial improvement in terms of THD and voltage regulation at Point of Common Coupling (PCC). [1] [3]

Table 4.10 Comparative Performance Analysis

Parameter	Without Compensation	Conventional DSTATCOM	Proposed BESS-DSTATCOM
Source Current THD	>20%	4–8%	2.95%
Power Factor	0.75–0.80 lagging	≈0.95	≈0.99
Voltage Regulation	Poor	Moderate	Excellent
Reactive Power Compensation	Not Available	Available	Highly Effective
Source Current Quality	Distorted	Nearly Sinusoidal	Balanced and Sinusoidal
DC-Link Voltage Stability	Unstable	Moderate	Highly Stable
Dynamic Response	Slow	Moderate	Fast
Transient Stability	Poor	Improved	Excellent
Harmonic Compensation	Not Available	Effective	Highly Effective
Renewable Intermittency Handling	Poor	Moderate	Excellent

The comparative study clearly indicates that the proposed Battery Energy-Storage-Integrated DSTATCOM offers significant improvement in overall power quality and microgrid stability. The obtained THD value of approximately 2.95% satisfies IEEE-519 harmonic standards and demonstrates effective harmonic suppression capability. [1] [3] [4] [12] [21]

The proposed system provides the following advantages over conventional compensation methods:

- Better harmonic mitigation [3]
- Improved voltage stability [21]
- Enhanced reactive power support
- Faster transient response
- Stable DC-link voltage
- Improved renewable energy utilization [16]
- Better handling of sudden disturbances

Therefore, the proposed Battery-Integrated DSTATCOM proves to be a highly efficient and reliable solution for power quality improvement in hybrid renewable microgrids under varying operating conditions. [1] [4] [12]

4.12 DISCUSSION OF RESULTS

Simulation outcomes obtained using the MATLAB/Simulink model have demonstrated the effectiveness of the proposed Battery-Energy-Storage-Integrated DSTATCOM in power quality improvement in the hybrid renewable microgrid. Performance of the system has been analyzed in different operating scenarios of nonlinear loading, intermittent renewable energy production, voltage disturbance, and sudden load changes. [1] [4] [12] [16]

Firstly, the system operates without any compensation and suffers from problems related to harmonic distortion, reactive power imbalance, voltage fluctuations, and low power factor because of nonlinear loading and intermittent renewable energy sources. In this case, the source current waveform experiences severe distortions and the level of THD is above permissible IEEE-519 limits. In addition, the system experiences unstable voltage profile and lower transient stability in dynamic operation mode. [3] [16] [21]

Conventional DSTATCOM significantly enhances system performance as far as it helps suppress harmonic components and compensate reactive power. At this point, the source current waveform turns into nearly sinusoidal curve while the system power factor considerably increases. Nevertheless, the system operates with relatively poor transient stability because of its inability to compensate fast dynamic changes of the system caused by sudden disturbances and renewables' output. [1] [3] [21]

Performance of the proposed battery-integrated DSTATCOM proves to be better compared to conventional DSTATCOM and uncompensated system. Integration of the BESS allows increasing active power compensation capability and ensuring higher levels of DC-link voltage stability under dynamic operating conditions. At that, control strategy applied on the basis of SRF theory enables extracting and compensating harmonic and reactive components of the source current. [1] [3]

According to FFT analysis, the level of source current THD is considerably reduced up to 2.95% and meets all IEEE-519 harmonic standards. Besides, the system successfully reduces reactive power demand from the utility source while significantly improving the level of source power factor up to almost unity. Other important advantages are fast transient response, minimal settling time, good voltage regulation, and increased stability during renewables' intermittency and load changes. [3] [21]

CHAPTER 5

FUTURE SCOPE AND CONCLUSION

5.1 CONCLUSION

- Summary of achieved objectives
- Key findings
- Improvement in power quality metrics [4]

In this work, a Battery Energy-Storage-Integrated DSTATCOM has been proposed and simulated for improving the power quality issues associated with hybrid renewable microgrids. In the proposed topology, renewable energy sources including PV system and wind energy have been incorporated into a Battery Energy Storage System and then integrated with a Voltage Source Converter Based DSTATCOM. [1] [4] [12] [16] [17]

This thesis focused on mitigating the major power quality problems such as harmonics, reactive power imbalance, voltage fluctuation, low power factor, and transient instabilities, etc. The proposed control method based on synchronous reference frame technique, PI controller, and PWM/hysteresis control methods for current control have been successfully implemented using Simulink/MATLAB software package. [3] [4] [16] [21]

According to the simulation results, the proposed Battery Integrated DSTATCOM system is capable of performing well and compensating the harmonic and reactive currents efficiently while stabilizing the DC link voltage. The source current waveform has been improved and become sinusoidal after compensation. Using FFT analysis, the THD of current waveform has been calculated to be around 2.95% satisfying IEEE-519 standard. [1] [3]

The use of Battery Energy Storage System resulted in higher transient stability and faster dynamic responses of the DSTATCOM. Due to the active power support from battery, the DC link voltage has been stabilized. Consequently, it has helped improving the voltage regulation and decreased settling time of the system. Furthermore, the source power factor has been greatly improved towards unity level due to the integration of battery. [1] [16] [21]

Comparison between conventional and proposed DSTATCOM shows that there are many benefits of using the proposed system including better harmonic compensation, fast transient response, improved voltage regulation, efficient reactive power compensation, and reliable system performance. [1] [3] [21]

It may thus be concluded that Battery Energy-Storage-Integrated DSTATCOM is a good candidate for solving the power quality problem of modern hybrid renewable microgrids.

5.2 CONTRIBUTIONS OF THE THESIS

The major contributions of the proposed thesis work are summarized as follows:

1. A comprehensive hybrid renewable microgrid model consisting of solar photovoltaic system, wind energy conversion system, Battery Energy Storage System (BESS), and DSTATCOM has been successfully developed in MATLAB/Simulink environment. [1] [12] [17]
2. A Battery Energy-Storage-Integrated DSTATCOM configuration has been proposed for effective power quality improvement in renewable energy integrated distribution systems. [1] [4] [16]
3. An efficient control strategy based on Synchronous Reference Frame (SRF) theory and PI controller has been implemented for harmonic mitigation, reactive power compensation, and voltage regulation. [3]
4. The proposed system successfully maintains stable DC-link voltage during renewable energy intermittency and sudden load disturbances through integration of Battery Energy Storage System. [16]
5. The developed DSTATCOM controller effectively compensates harmonic currents generated by nonlinear loads and improves the quality of source current waveform. [1] [3]
6. FFT analysis confirms that the proposed system reduces Total Harmonic Distortion (THD) to approximately 2.95%, which satisfies IEEE-519 harmonic standards. [3]
7. The proposed Battery-Integrated DSTATCOM significantly improves source power factor close to unity by providing effective reactive power compensation. [1]
8. The transient stability and dynamic response of the hybrid renewable microgrid are enhanced under varying operating conditions such as sudden load variation, voltage disturbances, and renewable power fluctuations. [12] [21]
9. Comparative analysis between uncompensated system, conventional DSTATCOM, and proposed Battery-Integrated DSTATCOM demonstrates superior performance of the proposed system in terms of: [1]
 - Harmonic suppression [3]
 - Voltage regulation
 - Reactive power support
 - DC-link voltage stability [21]
 - Dynamic response
10. The proposed system improves the reliability, stability, and overall power quality performance of the hybrid renewable microgrid, making it suitable for modern smart grid applications. [4] [12] [14] [21]

Therefore, the proposed thesis contributes toward the development of an efficient and reliable Battery Energy-Storage-Integrated DSTATCOM system for advanced power quality enhancement in renewable energy based microgrids. [1] [4] [12] [16]

5.3 LIMITATIONS OF THE PRESENT WORK

Though the above-discussed Battery Energy-Storage-Integrated DSTATCOM system shows considerable improvements in power quality and stability within the microgrids, there are some limitations associated with the proposed system. [1] [4] [12] [21]

1. The developed Battery Energy-Storage-Integrated DSTATCOM system has only been validated using MATLAB Simulink simulation study. No practical hardware implementation and experimental validation has been performed in this study.
2. The control mechanism implemented in the system primarily emphasizes on harmonic reduction, reactive power compensation, and voltage regulation. Optimization strategies of large scale renewable energy integration have not been considered within the system.
3. The BESS in this system has considered the operation within an ideal operating environment. Aging and other effects of the battery have been ignored while modeling BESS.
4. Solar Photovoltaic and Wind based renewable sources have been simulated in an ideal environment in this case. Real time uncertainties related to the forecast and environmental weather conditions have not been considered. [16] [17]
5. The proposed control strategy of DSTATCOM is implemented using the SRF theory and PI controller techniques. Advanced intelligence based control techniques, such as Artificial Intelligence (AI) and Machine Learning (ML), can improve the performance of the system in highly dynamic situations.
6. The proposed work has considered balanced three-phase networks. The performance of the system under extreme grid fault and other security issues of the smart microgrid have not been studied.
7. The economic analysis, cost optimization, and sizing of BESS and DSTATCOM devices have not been taken into account in this work. [1]
8. This study has considered a particular hybrid renewable microgrid structure. There is no study performed considering the simulation of interconnected smart grids and multiple microgrids within the network. [12] [14]
9. No effect due to the switching losses of power electronic converters in the simulation study has been considered.
10. There has been no practical validation of the proposed system by hardware-in-loop simulation, FPGA, DSP, or OPAL-RT simulations.

Though the above limitations have been seen in the proposed system, the system has demonstrated considerable improvement in terms of harmonic mitigation, reactive power compensation, voltage regulation, and transient stability of hybrid renewable microgrid systems. [1] [3] [12] [21]

5.4 FUTURE SCOPE

- AI-based adaptive controllers
- Hardware implementation
- Real-time OPAL-RT validation
- EV integrated microgrids [12]
- Smart grid applications [14]

Despite demonstrating successful power quality improvement and stable hybrid renewable microgrid operation, there are some other research areas that require further investigation related to Battery Energy-Storage-Integrated DSTATCOM. The potential areas for future study can be listed as follows: [1] [4] [12]

1. The use of intelligent control strategies and algorithms like AI, machine learning, ANN, ANFIS, and deep learning algorithms can contribute to the enhancement of dynamic performance and adaptability of the DSTATCOM controller. [1] [8]
2. Hardware implementation of the proposed system in FPGA, DSP, dSPACE, OPAL-RT, or any other similar technology platform can help in practical validation and real-life application.
3. Hardware-in-loop (HIL) simulation experiments and test results will give an opportunity to assess the practical operation of the proposed battery-integrated DSTATCOM system under different real-life operating conditions. [1]
4. Considering various issues of batteries, advanced battery management systems accounting for battery aging, battery life cycle, thermal characteristics, and SOH estimation algorithms can be included in the system to achieve higher efficiency and reliability.
5. The incorporation of electric vehicle charging station infrastructure into the Battery Energy Storage System (BESS) and DSTATCOM in order to increase the scope of their usage in future smart grids and renewable energy applications can also be considered. [1] [14]
6. Development of multi-microgrid and interconnected smart grid systems where the proposed system is applicable can be explored further for renewable energy sources integration.
7. Special attention should be paid to implementing AI-based renewable energy forecasting models to make energy management of BESS more efficient.
8. Tuning of the controller of the proposed system using optimization techniques such as PSO, GA, WOA, etc. and BESS capacity optimization can improve the system performance.
9. Effects of communication delays and cybersecurity problems in smart microgrid environments can be explored in the context of ensuring reliable power supply.
10. The development of hybrid energy storage systems utilizing supercapacitors, hydrogen storage devices, fuel cells, and other storage technologies in combination with DSTATCOM is another promising future direction. [1]
11. The application of the suggested control strategy to grid-connected renewable power plant facilities, industrial power generation, electric railway systems, and distributed smart grid applications is also relevant in terms of comprehensive power quality improvement. [4] [14]
12. It would be interesting to consider methods of minimizing switch losses and increasing converter efficiency, and develop more cost-effective compensation techniques for DSTATCOM.

Thus, advances in intelligent control, energy storage technologies, and real-time implementation tools can contribute to even further improvement of the proposed Battery Energy-Storage-Integrated DSTATCOM system efficiency and application range.