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Review

A Comprehensive Review: Mitigating Techniques for Power Variability Due to Integration of Renewable Energy Sources With Grid

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Abstract: Renewable energy sources like solar panels and wind turbines are becoming more important for generating power. The inconsistent and unreliable output of solar panels and wind turbines is due to factors like clouds, weather conditions, and wind speed that cause their energy production to fluctuate. Connecting intermittent sources to the utility grid creates difficulties in different technical areas, such as ensuring a steady and reliable power supply, protecting the system from disruptions, controlling the distribution of generated power, and maintaining a consistent level of power quality. In this situation, adjusting the amount of electricity produced by an intermittent energy source to keep the power grid stable is essential. This issue must be resolved as soon as possible. The extension to these locations diminishes the grid's strength. It leads to a scenario where a solar power plant is integrated into a subpar electric grid. However, integrating solar power into a shoddy AC infrastructure has problems with power quality (PQ) problems, which restricts penetration levels. This review article suggests various FACTS devices and various conventional, adaptive, and AI-based algorithms to reduce PQ issues brought on by a weak grid and increase renewable energy source (RES) penetration levels. This paper discusses the PQ issues that occur when RES like solar power plants (SPP) and wind power plants (WPP) or both as hybrid are connected to the electrical grid. It also explores different ways to reduce the fluctuation in power output from the solar panels. It analyzes the numerous power quality issues that arise with solar penetration and PQ mitigation methods using several FACTS devices and control algorithms, including traditional control, adaptive control, and AI-based control algorithms. For the benefit of engineers and academics working in this field of study, various research publications have been carefully evaluated, organized, and placed on this paper for convenient reference. It also briefly discusses the plan for controlling battery storage system for solve this problem.

***Keywords*:** hybrid energy generation system (HEGS), wind energy generation system (WEGS), solar energy generation system (SEGS), energy storage system (ESS), control technique, power fluctuation and smoothing PV output.

1. Introduction

Continuously, distributed generating systems employing renewable energy replace centralized systems based on fossil fuels in producing electrical electricity (RE). As a result, utility grids are adopting RE to satisfy anticipated future energy demand. The primary drawback of RE is that they cannot be dispatched. It causes the output of RE generation to vary according to meteorological factors like sun radiation or wind speeds [1]. It causes a mismatch in the timing of supply and demand. The battery energy storage device can be used to control this temporal mismatch. The most popular renewable energy source is solar energy. Utility grid disruptions

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become common when solar energy is present. It can mitigate this energy storage device to balance the intermittency. Either the load on the grid decreases, or the extra PV electricity is stored.

Conversely, it releases when the demand increases, or PV stops producing power [2]. Today, small-scale installations of solar energy generation systems (SEGS) and wind energy generation systems (WEGS) are widespread. Both photovoltaic energy (PVE) and wind energy (WE) have developed and are now widely used. A hybrid energy system produces electricity by combining two or more unconventional energy sources [3]. It is a fantastic strategy for electricity distribution. One of this technology's primary advantages over traditional energy-producing systems is that it is located near the load or connected to the utility grid. This assessment's hybrid energy generation system uses wind and solar energy [4]. By using a rectifier and synchronizing with a solar energy generation system, a wind turbine transforms the mechanical power of the wind into electrical power (SEGS). Before connecting this HEGS to the grid, we must convert the DC voltage produced by the solar PV array into AC. The Researcher must use a DC-link capacitor to maintain a consistent DC voltage at the input side of the voltage source inverter. The output of a hybrid system is converted into AC via VSI, which also interfaces with the grid. The grid-connected technology is more dependable and can continuously supply electricity to the utility grid, although wind and solar energy production are unpredictable and occasionally uncontrolled. An Energy Storage System could be employed to solve this issue. Power system operation, control, and management heavily rely on energy storage systems [5]. Overall solar power generation between 20013–2022 [6] is depicted in Figure 1. As documented by the investigators, some of the problems with RES output power fluctuation brought on by cloud movement are listed below.

- As PV penetration rises, conventional generator generators find it challenging to keep up with the rapid shift in PV generation.
- When the PV output power changes abruptly, the area control error of two or more linked areas may exceed the permissible limit.
- Significant uncontrolled PV penetration may alter the utility's dispatch of regulating units, violating the dispatch regulating margins.
- The system's overall operating costs rise due to frequent variations in PV production brought on by changes in a cloud pattern.

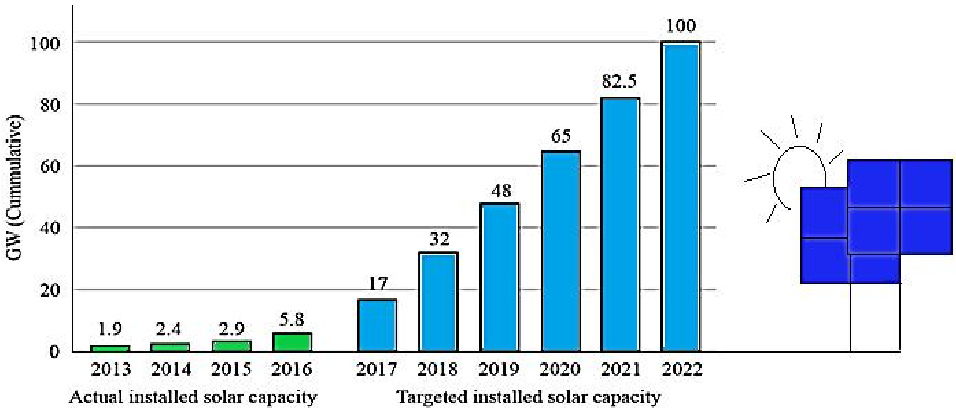


Figure 1. Overall Solar power generation between 2013–2022.

This paper aims to comprehensively review the problem associated with intermittent renewable energy sources (RES) output when connected to the grid and its mitigation techniques. Firstly, the paper discusses a few crucial issues caused by renewable energy source's output variability when solar is connected to the grid. Then, a brief explanation of smoothing output power fluctuation by geographical dispersion for PV clusters installed in vast areas is presented. Then comprehensive discussion on methods of mitigating RES output power fluctuations for individual PV installation using batteries, capacitors, electric double layer capacitors (EDLC), superconductive magnetic energy storage (SMES), diesel generators, fuel cells, MPPT power curtailment and dump loads is reviewed in detail. Based on a comparative analysis of these various mitigation methods, it was found that batteries are the ideal choice for this fluctuation problem. Therefore, the control strategy of battery energy storage is also discussed briefly. The paper is organized as follows: Section 2 addresses the problem when the output power of RES fluctuates, Section 3 explains the ways to develop a hybrid energy generation system (HEGS) from RES, Section 4 explains the ways to smooth the output power fluctuations from HRES, Section 5 explains control strategy for optimistic operation of battery storage system to solve this problem. Discussion is presented in Section 6, and this paper is concluded in Section 7.

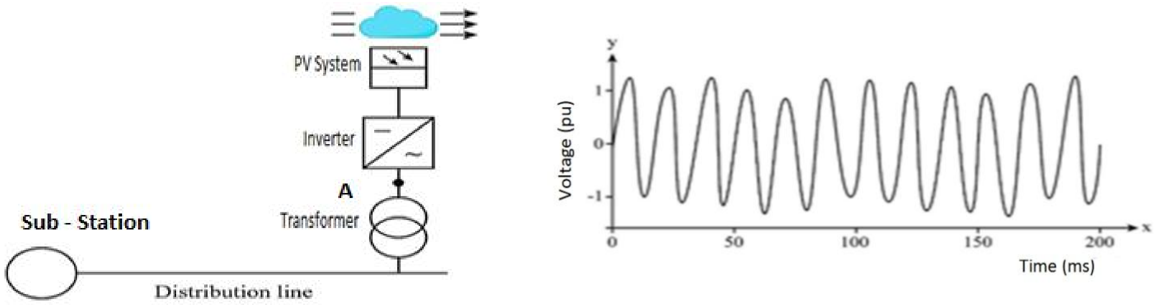
2. Problems With Intermittent RE Power Source

Installing PV in the feeder would exacerbate frequency deviation and voltage fluctuation in the electric power system [7]. Essential topics covered in this section are.

- Grid-connected voltage fluctuation
- Voltage rise and reverse power flow
- Unplanned islanding
- Power fluctuation in the grid
- Influence on grid frequency.

2.1 *Grid-Connected Voltage Fluctuation*

An alteration from the advised voltage is called voltage fluctuation. When it goes beyond the set limit, it becomes an issue. PV both influences and sometimes contributes to grid voltage fluctuations. Although cloud movement can also cause induced voltage fluctuations, cloud cover has no bearing on the size of the fluctuations, as seen in Figure 2. Voltage variations' effects have been described [8] and are illustrated in Figure 2a and 2b.



(a) (b)

Figure 2. Cloud-induced voltage flicker issue.

2.2 *Voltage Rise and Reverse Power Flow*

Voltage regulation becomes a concern when the grid's usage of sporadic power increases. As PV penetration increases, so does the substation's voltage level [9]. The constraints may be exceeded if capacitor banks or voltage regulating devices are present, often put in substations to boost the voltage. Limiting the production of actual PV power is one potential solution to this problem [10]. The voltage will rise when power is reversed from the sporadic source and is directed toward the substation when a collection of sporadic PV systems is connected to a low voltage (LV) distribution network [11]. The intermittent power source has to be unplugged from the LV network while the voltage rises. The power output from the PV should also be limited during this time. The issue of local voltage escalation is illustrated in Figure 2 [12]. As the distribution line travels from the sub-station to the PV connection point, the voltage across it lowers. Figure 2 depicts the problem of voltage rise locally. The voltage across the distribution line decreases from the sub-station until it reaches the point of the PV connection. The voltage rises immediately after connecting PV at points A and B. To avoid further voltage, rise beyond its acceptable upper limit. The PVs at points C and D are disconnected, as reported in Figure 3. In addition. Reverse power flow destabilizes the control system of voltage regulators since they are designed for unidirectional power flow and also trigger the protection relay, which may disconnect the load. Also, reverse power flow throws off their control systems because voltage regulators are designed for unidirectional power flow. A safety relay is also turned on, which might disconnect the load [13].

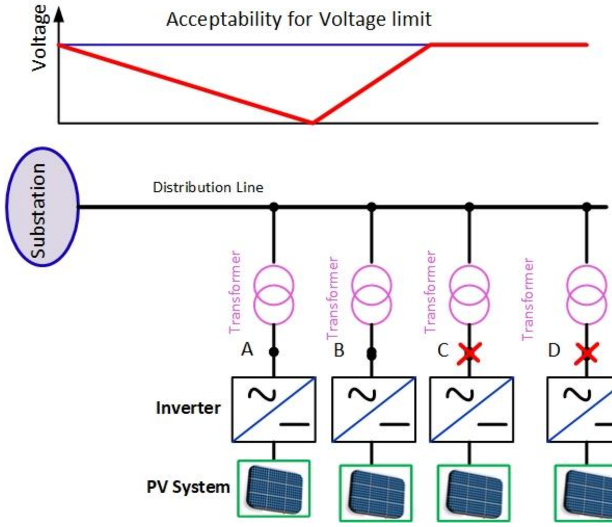


Figure 3. Issue of voltage rise at distribution network.

Authors have suggested solutions for the distribution network's reverse power flow issue. The authors advised phase balancing on the utility side [14] as a way to reduce single-phase reverse power flow. It was also advised to use bidirectional regulators to keep the voltage under control and stop three-phase reverse power flows. The distribution system's performance might be improved by reactive power regulation for the PV inverter, according to the authors [15]. Reactive power regulation reduces the voltage fluctuation in the distribution system brought on by transient solar power. Other solutions to the voltage increase issue were offered in the literature, including dump loads and energy storage systems. The authors proposed local management of the PV inverter to prevent voltage increases from reducing both active and reactive power [16]. Voltage flicker is a significant issue when PV power generation changes. A change in voltage peaks in the waveform seen in Figure 2a caused by a change in PV output power caused by cloud movement is exemplified by voltage flicker in Figure 2b. This issue arises when PV brings unexpected voltage fluctuations that rapidly vary due to passing clouds. The voltage rise problem has numerous solutions, according to the literature [17].

2.3 *Unplanned Islanding*

When a problem in the distribution level occurs, and the power produced by the PV is equivalent to the load demand, this is known as unintentional islanding. The PV system cannot detect the grid power outage and thus keeps producing electricity for the load [18]. However, the PV system must stop producing energy due to safety concerns. Unintentional islanding is the name of this condition. Unintentional islanding can be discovered via remote, active, and passive techniques [19]. The utility-side remote islanding technique requires communication between the utility and the PV inverter unit. Despite being more dependable, it involves complicated communication mechanisms and is more expensive to install than active and passive systems. The islanding is detected when employing the active technique by purposefully producing a grid disruption, such as active or reactive power fluctuations [20]. However, these interruptions also impact the quality of the electricity. The efficiency of PVs when linked in a cluster, the efficiency of PVs may also be affected by these intentional disturbances. When islanding occurs, the passive island detection approach searches for a sudden change in variables such as voltage, current, frequency, and active or reactive power. The passive technique works well for extensive power systems when the enormous parameter drift is apparent [21].

2.4 *Power Fluctuations in the Grid*

When there is a grid disruption, many different industries are impacted. The intermittent power production from solar and wind power sources is one of the primary sources of disruption. Unlike nuclear, thermal, or gas-fired facilities, these sources do not continually supply a steady amount of electricity [22]. The capacity of the grid operator to forecast the amount of electricity generated by these sporadic sources is a challenge. Due to the grid's irregular behaviour, changes in voltage and frequency characteristics affect sensitive gear in industrial plants. Due to this issue, it is common practice to deploy local generators and battery backups to safeguard delicate equipment and control systems [23].

2.5 *Grid Frequency Impact*

One of the critical components of electricity quality is frequency. It is necessary to maintain constant frequency during grid hook-up. Frequency variation in the grid is usually caused by demand fluctuation, and it worsens when PV output power swings rapidly owing to changes in radiation level [24]. Control of intermittent source output is required since a higher proportion of PV will impact the quality of the electricity during grid hook-up. The frequency deviation from PV penetration is less than wind turbines since wind units now have a bigger installed capacity than PV. Installing energy storage equipment will allow the frequency to be controlled. Charging or discharging the storage at the operator's request may utilize distributed storage to control the region's system frequency. Future frequency variation from greater PV penetration will be apparent [25].

3. Hybrid Energy Generation Systems (HEGS)

The need for energy is rising daily, but neither the conventional nor the individual nonconventional sources that are now accessible can meet the needs of consumers. This hybrid power production system can be employed in distant or hilly places where traditional power generation is practical to bridge the gap between supply and demand during peak demand [26]. This paper reviews wind-photovoltaic energy generating and storage systems by analyzing many research publications. Power is produced through a hybrid energy production system that combines SEGS and WEGS. The following are included: ESSES, DC-Link, Converter, Inverter, Etc. If one fails, the utility grid and consumer loads may still be powered by the second power supply system, making it more advantageous when one power-producing system is unreliable [27]. This hybrid system comprises several parts: an inverter, ESS, DC-to-DC converter, and PV-wind generation system. The fundamental block diagram may be seen in Figure 4. As a result of the intermittent nature of wind and solar power generation and their dependence on meteorological conditions, energy storage systems (EESS) are a fundamental technology that is crucial in the modern day.

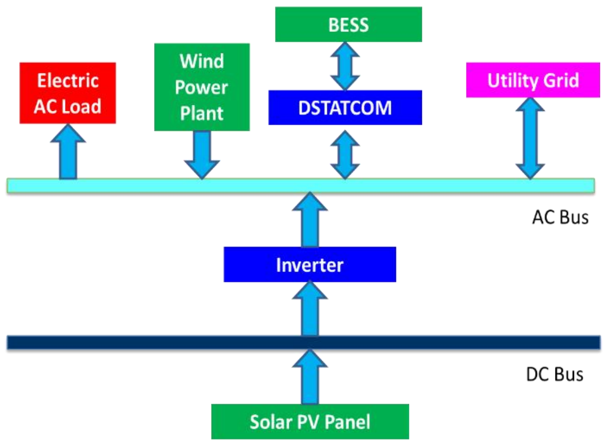


Figure 4. Modern approach for hybrid power system with energy storage system.

4. Mitigation of Power Variability in Hybrid Power Distribution Network

The system will attempt to monitor the reference power signal of output power with the power imbalance that the smoothing algorithm creates by averaging a given set of data over a certain period.

4.1 *Power Smoothing of Wind Power*

The intermittent nature of solar and wind generation may impact the safe and dependable operation of the low-voltage grid. Therefore, they must be smoothed out the electricity before being injected into the electrical system. The Li-ion battery with a power smoothing algorithm based on moving average functionality is the suggested remedy in this study (MAF) [28]. The reference for the Li-ion battery's charge or discharge is represented by reference power between the reference power signals received via the Pout smoothing method and the produced power hybrid [29], depicted in Figure 5.

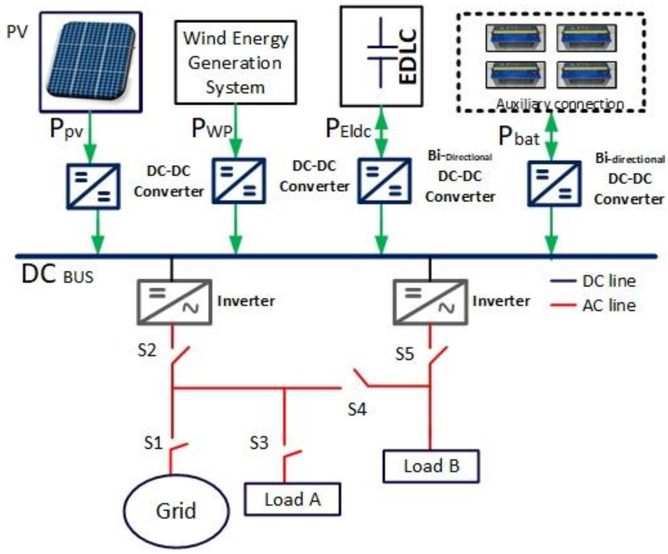


Figure 5. Structure of PV, EDLC, WEGS dispersed system.

4.2 *Dstatcom Using BESD*

An integrated distribution static compensator with a three-leg topology, three-phase, three-wire design, and a battery energy storage device is included on bus B2 of the test system. The rated capacity of the BESD is 7200 Ah. The battery bank, dc-link capacitor, ripple filter, and DSTATCOM coupling inductor characteristics are used in the suggested study. Synchronized reference frame theory controls the energy storage device via a DSTATCOM interface [30].

4.3 *Smoothing by Using Battery Energy Storage*

Energy storage solutions will inevitably be used as grid PV adoption rises. Battery energy storage (BES) uses a network of multiple series-parallel batteries to provide the necessary power for the application. Batteries may store energy in an electrochemical process and are reasonably priced [31]. In both charging and discharging modes, they react quickly. Batteries of various types: (i). Flooded lead acid, (ii). Lead acid regulated valve, (iii). Nickel-cadmium (iv). Lithium-ion, (v). Sodium sulfide. (vi). Vanadium redox batteries are used in BES applications. Due to their inexpensive price and extensive availability on the market, lead acid (LA) batteries are frequently employed. A few drawbacks of LA batteries include increased maintenance costs and the need for repeated additions of distilled water [32]. Figure 6 represents the battery station of a grid-connected solar PV system.

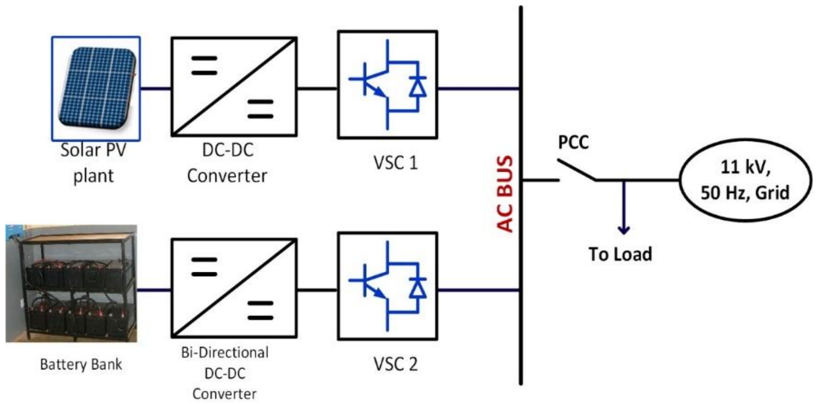


Figure 6. The battery station is linked to the grid to regulating PV output.

4.4 *Buck-Boost Converter Control*

Controlling the buck-boost controller enhances the power transfer between the capacitor and PV, as illustrated in Figure 7. By activating and deactivating the pulses G1 and G2, the capacitor may inject or absorb power. An innovative concept for managing voltage in the distribution system through collaboration between the operator of the distribution network and commercial clients is illustrated. Installing a Static Var Compensator (SVC) might vary the voltage of the distribution network in response to variations in PV output (SVC). PV output is used to conduct an analysis based on minute-by-minute irradiation data [33].

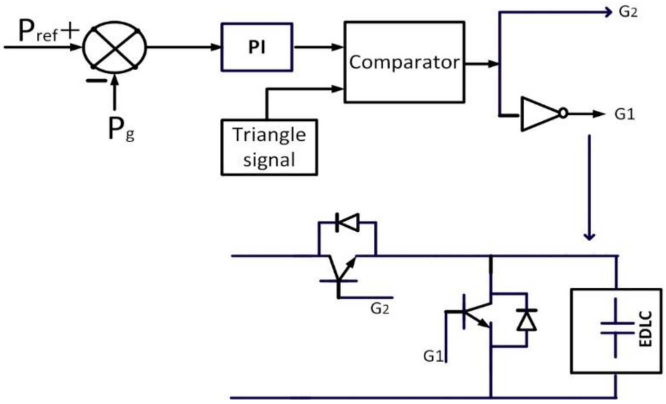


Figure 7. Buck-boost converter control.

4.5 *RE Is Coupled to the Power Grid via a Dump Load*

Dump loads are primarily installed to absorb extra electricity PV systems produce and smooth out irregularities. A controller controls the power flow via the resistance-based dump load as depicted in Figure 8. A loss occurs when power is wasted somehow. The authors investigated the effect of voltage fluctuation and flicker as clouds pass over solar panels. As a result, the distribution network experiences significant voltage flickers caused by passing clouds. The number of flickers is higher than what is recommended [34].

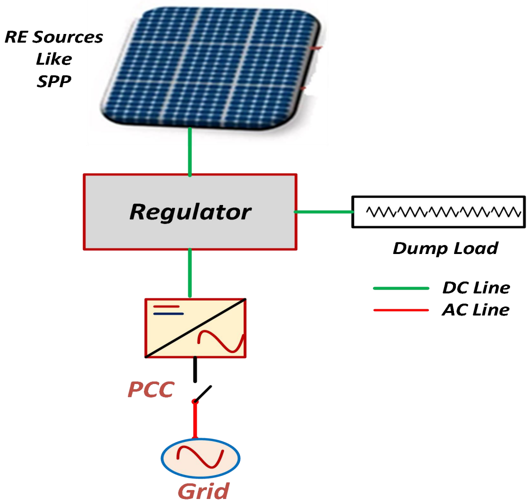


Figure 8. Grid-connected solar renewable energy source with DC dump load.

5. Control Strategy for Optimistic Use of Battery Storage System

For the BES to build a control plan, it is vital to comprehend battery Modelling. Building the BES using a basic battery model is straightforward but needs to be more accurate. When creating the battery's rule-based control, the charging/discharging current limit, battery life, and battery SOC limits are considered. Since the rule-based control constantly receives feedback from the BES, it is regarded as a closed-loop optimum controller. This controller's benefit is that it is simple to use and takes less time to compute than other controllers because it does not need to solve mathematical equations. The suggested controller may be used for any energy storage method by including its limitations, as depicted in Figure 9a.

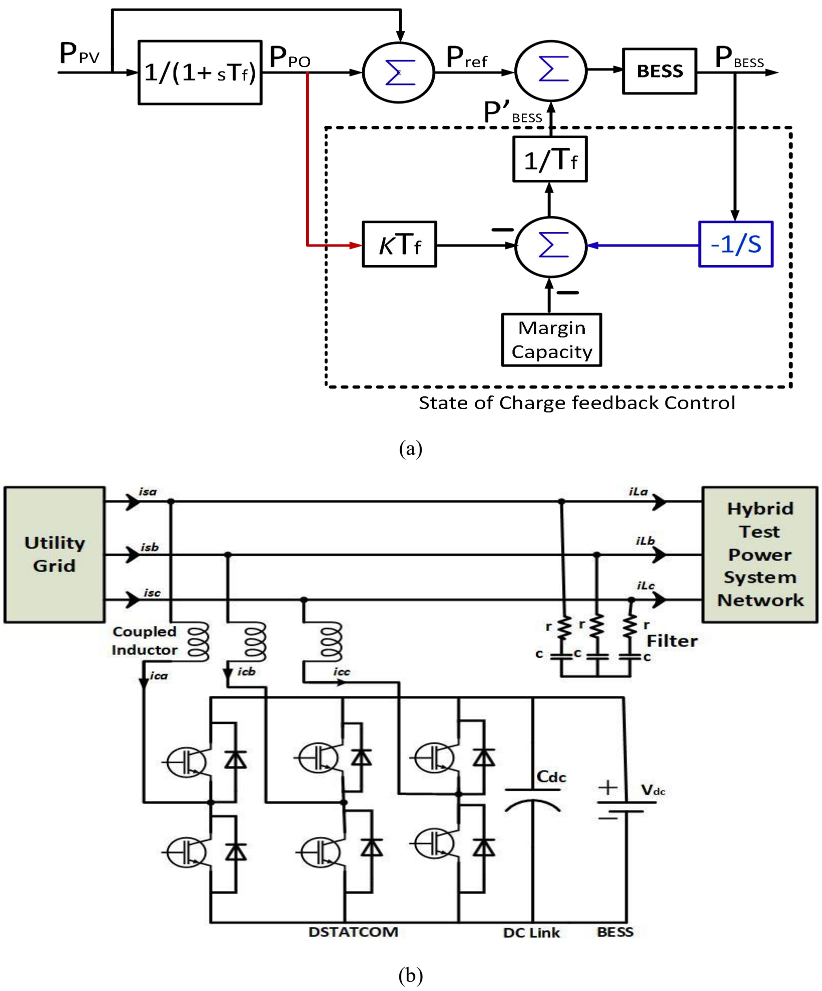


Figure 9. Control strategy for battery storage system supported by DSTATCOM for mitigating power variability (a) SOC-feedback controller (b) Power exchange by BESS.

The outer control loop produces the direct and quadrature axis reference currents. The SOC feedback controller produces the battery reference power, which serves as the input to the outside control loop. Here, the evolutionary algorithm is used to optimize the SOC time constant (TSOC), SOC margin rate (M), and BES energy rating (CBES) in the SOC feedback controller. This work's key objectives were to (i) make the BES smaller, (ii) Identify the BES's ideal charge/discharge level, and (iii) make sure the BES is operated safely [35–38]. The BESS-supported DSTATCOM is connected to the bus of the test system. The circuit breaker connects a wind generator and Solar Generator to the bus. The voltage at the bus and current flowing between the utility grid and test system are continuously tracked with the help of an SRF theory-based controller. An error signal is generated based on the reference source current and captured source current. This error signal is utilized to generate the PWM signals for gating the IGBTs of the VSC, which controls the active and reactive power flow between the PCC and BESS-supported DSTATCOM. The error signal will be generated depending on the variations in the standard values of voltage and current. Hence, the SRF theory-based control of DSTATCOM with BESS can be effectively utilized for grid-level PQ improvement under various case studies [39–41].

6. Discussion

In this paper a novel promising multilevel inverter was introduced. The number of components and DC supplies was reduced while keeping a high number of output voltage steps and reasonable THD, the main approach to do that was by combining a DC voltage summing and subtracting circuit with a circuit that divides the DC voltage by two.

In order to address the PQ issues raised by greater penetration of solar power into rural grids as a solution for "access to energy," this paper gives a comprehensive examination of approaches. By introducing IEEE standards for various PQ events, the Configuration of various DSTATCOM devices, and the control algorithms utilized for grid integration of RE systems, this paper offers a launch pad for aspiring researchers. Additionally, it offers mathematical representations of each control algorithm employed by the DSTATCOM devices. For those who are interested in working in this field with various configurations and scenarios of RE integration into a weak grid, a comparative performance analysis of several control techniques has been offered. The most popular option for MW-scale RE systems is battery energy storage since batteries have a high energy density and can discharge electricity for hours. Smaller RE systems can use capacitors or SMEs, which have a high power density and a quick power discharge time, to mitigate power fluctuation. Increased energy density is crucial for capacitors or SMEs, and this restriction prevents their use in multi-MW scale RE systems. The reasoning above shows that battery energy storage supported FACT device DSTATCOM is the best choice for hybrid power system (HPS) of any size to lessen fluctuations in output power as reported in Table1.

Table 1. Comparison of the characteristics of several mitigation strategies for minimizing RE power fluctuation.

Characteristics	DSTATCOM supported BESS	ELDC/SME /Capacitor	Diesel generator	MPPT method	Fuel Cell	Dump load	Natural gas engine generator
Response time of the source for an issue with mitigation	Fast	Very fast	Slow	Fast	Slow	Fast	Slow
Application for short and long-term storage	Short	Short	Long	Long	Long	Long	Long
Capability to manage rapid ramp-ups and ramp-downs	Yes	Yes, very rapid	No	Yes	No	Yes	No
Effectiveness in reducing transient RE power fluctuations	High	High	Low	High	Low	High	Low
Ability to regulate voltage/frequency fluctuations brought on by grid-side RE power fluctuations	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Capable of reliably reducing RE power fluctuations	High	Very high	Low	High	Low	High	Low
Cost	High	High	High	Low	High	Low	High
Size of RE plant	0–MW scale	0–kW scale	0-MW scale	0-kW scale	kW-MW scale	0-kW scale	kW-MW scale

7. Conclusion

In order to address the PQ issues raised by greater penetration of solar power into rural grids as a solution for "access to energy," this paper gives a comprehensive examination of approaches. By introducing IEEE standards for various PQ events, the Configuration of various DSTATCOM devices, and the control algorithms utilized for grid integration of RE systems, this paper offers a launch pad for aspiring researchers. Additionally, it offers mathematical representations of each control algorithm employed by the DSTATCOM devices. For those who are interested in working in this field with various configurations and scenarios of RE integration into a weak grid, a comparative performance analysis of several control techniques has been offered. For those who are interested in working in this field with various configurations and scenarios of RE integration into a weak grid, a comparison of the performance of various control methods has been offered. DSTATCOM has been determined to operate better than other FACTS devices in terms of load balancing, transient stability, and effective reactive power compensation, according to observations. In order to meet IEEE standards, it has also been discovered that adaptive signal processing-based control algorithms with lower computational complexity, higher accuracy, and adaptiveness work in conjunction with DSTATCOM to offer precise, affordable, and effective solutions to the PQ problems brought on by higher SPV penetration levels onto the rural grid. Researchers working on international missions like the Carbon Dioxide Removal (CDR) program's mission and the green-powered future mission, as well as national missions (NSM) like the Jawaharlal Nehru national solar mission (JNNSM) and Swachh Bharat mission, could use this article as a guide. An updated review of the various methods for reducing output power fluctuation from RE sources is provided in this publication. The use of storage technologies like batteries, capacitors, and fuel cells is essential and has been found to be very effective in reducing the changes in RE output since intermittent sources are connected to the grid. The application of fuel cells to this issue is still in its infancy. Power quality applications might also make use of batteries or capacitors.

Researchers can experiment with the effects of using batteries, capacitors, or any other additional sources put separately or in a single location to reduce RE variability for geographically spread RE sources. Strategic deployment of energy storage technology for distributed REs can also be investigated. Well-placed energy storage devices can help to tackle additional problems like voltage fluctuation and voltage flicker caused by RE output variability.

Research on the problems with grid-connected power quality brought on by variations in RE output is source. A significant portion of the literature focuses on smoothing RE output. When adjusting RE output power, it is necessary to pay more attention to voltage flicker, voltage at the grid side, reverse power flow, and frequency deviation. Solving these power quality problems requires special consideration. Forecasts for sun radiation determine how successful these mitigation measures will be. To anticipate solar radiation from which RE output power is computed, a more straightforward and precise technique is required. Operators of plants that can schedule conventional generators will find these strategies beneficial. Increased RE penetration causes grid issues, however the increase of solar energy generation shouldn't be constrained by the issues.

Conflict of Interest

There is no conflict of interest for this study.

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