Using Shunt Capacitors to Mitigate the Effects of Increasing Renewable Energy Penetration

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ABSTRACT

Over the past two decades, Renewable Energy Sources (RESs) have gained global popularity. Control issues are becoming more difficult as the system inertia decreases due to the absence of typical synchronous generators. Innovative methods like fault current limiters, energy storage devices, and alternative control systems are utilized to deal with these difficulties. This study provides a summary of the challenges associated with incorporating high-level RESs into the existing grid. The increased penetration of the RESs has a negative impact on the system oscillations and harmonics, generating the need for power quality improvement techniques, such as adaptive control, adding energy systems, power stream assessment, or weight stream examination. This paper presents a framework of the power stream issue, its arrangement as well as different game plan methods. The power stream model of a power structure can be built using the significant association, weight, and age data.

Keywords-Renewable Energy Sources (RESs); high-level RES penetration; power quality; shunt capacitor

I. INTRODUCTION

Emissions from fossil fuel-based power plants, including carbon dioxide, sulfur dioxide, and nitrogen oxide, have raised multiple environmental concerns recently. Renewable Energy (RE) generation technologies, in contrast to conventional synchronous machine-based power generation approaches, are regarded as cleaner and less expensive. As a result, governments and a wide range of organizations are striving to boost RE production in order for it to replace the power generation based on fossil fuels [1, 2]. The International Renewable Energy Agency claims that there is a plan for integrating RE around the world up until 2030, with Renewable Energy Sources (RESs) being expected to supply 36% of the world's energy needs by that time [3]. The most promising RESs are the solar and wind energy harvesting systems, which can determine maximum power points over a broad range of variations in wind and solar irradiation. Until 2009 more money was invested in wind power generation [4, 5], a fact which, however, has been reversed.

High-level integration of RESs into the utility grid may cause problems with system stability and reliability because of the stochastic nature of power generation, due to the fluctuations in wind speed and solar irradiance. RESs' intermittent and unpredictable nature could be effectively modeled to reduce the detrimental influence on system stability [6, 7]. A number of modeling approaches for uncertainties in RE are described in the literature. The Power Electronic (PE) converters connected to the RESs must be carefully regulated in order to allow for stable operation during transients and variations in the AC system parameters. RESs should remain connected during system failures in accordance with grid code requirements. [8-10]. Therefore, it is essential to enhance the RE conversion systems' fault ride. The literature has provided numerous methods for ameliorating the capabilities of grid-connected solar and wind energy systems. [11, 12]. Expensive PE converters are required for power conditioning in RE conversion systems. This type of converter needs to be safeguarded from an economic and stable perspective [13, 14]. Conversely, as the number of RESs increases, short-circuit power levels increase. To keep the fault current below the allowable limits, various solutions have been proposed, including fault current limiters, energy storage devices, and dynamic voltage restorers.

II. THE KUNDUR SYSTEM

The "Power System Stability and Control" textbook by Prabha Kundur [17] is the source of the two-area system test case. It provides a standard for researching oscillation damping, power exchange, dynamic stability, and related topics. Eleven buses and two areas make up the system, which is connected by a weak tie between buses 7 and 9. Buses 7 and 9 have two loads applied to them, and these buses are also connected to two shunt capacitors. The system consists of two identical areas connected by a weak tie and it runs at a fundamental frequency of 60 Hz. Table I shows the power flow data of the system.

TABLE I. PSSE POWER FLOW DATA

Bus no.	Bus name	Base kV	Area no.	Area name	Zone no.	Code	Voltage (pu)	Angle (deg)
1	GEN G1	20	1	LEFT	1	2	1.03	20.07
2	GEN G2	20	1	LEFT	1	2	1.01	10.31
3	GEN G3	20	2	RIGHT	1	3	1.03	-7
4	GEN G4	20	2	RIGHT	1	2	1.01	-17.19
5	G1	230	1	LEFT	1	1	1.0065	13.61
6	G2	230	1	LEFT	1	1	0.9781	3.52
7	LOAD A	230	1	LEFT	1	1	0.961	-4.89
8	MID-POINT	230	1	LEFT	1	1	0.9486	-18.75
9	LOAD B	230	2	RIGHT	1	1	0.9714	-32.35
10	G4	230	2	RIGHT	1	1	0.9835	-23.94
11	G3	230	2	RIGHT	1	1	1.0083	-13.63

A. Simulation Results

The impact of high renewable energy generation (and Voltage at bus 8) (line fault from bus 7 to 8) can be seen in Figure 1. In Figure 2, we can see the system response when it becomes unstable. The clearing time is 0.07 s (line fault from line 7 to 8).

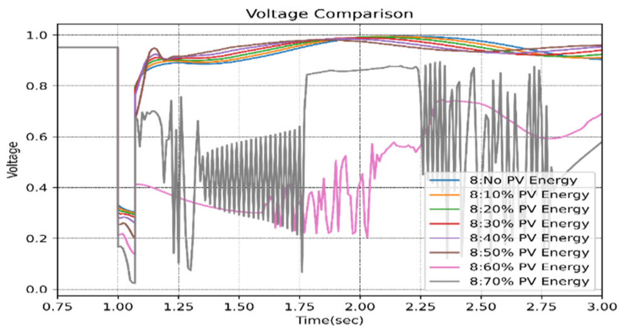

Fig. 1. Voltage comparison at bus 8 for high renewable energy generation.

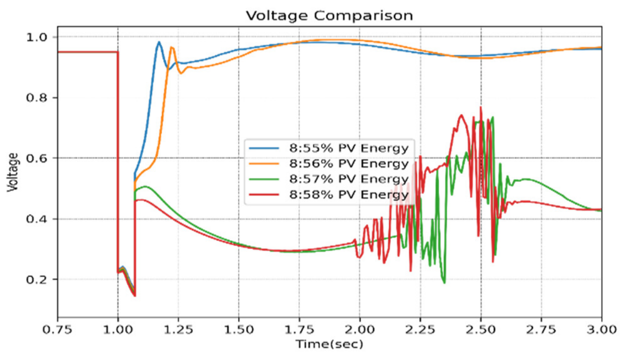

Fig. 2. Voltage Bus 8 for system fault.

The Voltage drops in this case can be seen in Table II.

TABLE II. VOLTAGE DROP BETWEEN 55% TO 58%

PV energy	Voltage drop	status
55%	0.1637423038482666	stable
56%	0.15722447633743286	stable
57%	0.12031149864196777	unstable
58%	0.11727101355791092	unstable

The power flow result in the case when not using capacitors can be seen in Table III.

TABLE III. POWER FLOW WITHOUT CAPACITORS IN 60% PV

NO Pv energy (without Cap)				
BUS	NAME	BASKV	VOLT	ANGLE
1	GEN G1	20	1.03000	19.8
2	GEN G2	20	1.03000	10.2
3	GEN G3	20	1.03000	-7
4	GEN G4	20	1.03000	-17.2
5	G1	230	1.01277	13.4
6	G2	230	0.98094	3.4
7	LOAD A	230	0.96392	-5
8	MID POINT	230	0.95062	-18.8
9	LOAD B	230	0.9721	-32.3
10	G4	230	0.98388	-23.9
11	G3	230	1.00843	-13.6

III. POWER QUALITY ISSUES

PE converters serve as the core of RE systems, managing harmonic injection and ensuring high-quality voltage signals. The power quality of RESs is improved by the use of various devices, such as auxiliary devices and more beneficial control strategies. To address power quality issues in PV/wind systems, more advanced filtering technologies are utilized, such as active and passive filters. However, as converter power ratings increase, passive filters become costlier, larger, and heavier, making them ineffective for advanced technologies. To compensate for reactive power and current harmonics and enhance power quality, Shunt Active Power Filters (SAPFs) are a promising alternative. As RE penetration increases, the size of Active Power Filters (APFs) grows accordingly. Hybrid APFs offer a solution by reducing filter size and cost. These hybrid filters combine SAPFs to eliminate lower-order harmonics and passive filters to address higher-order harmonics. Harmonics at switching frequency and its multiples pose challenges for RE converters, prompting the proposal of higher-order active filters with minimal voltage drop and compact component size [15, 16].

The hybrid generalized integrator controller is employed in an enhanced high frequency harmonics rejection approach. The controller lowers disturbances, subharmonics, and inter-harmonics despite a trade-off between accuracy and convergence speed. A dynamic state estimate based sliding mode control is presented for grid-connected solar farms that can improve power quality and decrease unnecessary converter switching. For hybrid PV/wind systems with no filter or auxiliary devices, some control strategies for improving power quality are offered. To achieve fundamental load component extraction and harmonic compensation, a new Least Mean Mixed Norm (LMMN) control approach is adopted [16].

Various Flexible AC Transmission Systems (FACTS) devices like Thyristor-Controlled Series Capacitors (TCSCs), Static VAR Compensators (SVCs), and Static Synchronous Compensators (STATCOMs) are proposed to mitigate harmonics, voltage dips, power factor and electrical oscillations in renewable energy systems. Gaps in methodologies are identified, providing insights for future research. Additionally, energy storage technologies, such as batteries, super capacitors, and flywheel energy storage are utilized to smooth power fluctuations. A sophisticated power allocation system between PV and battery storage is developed in order to support reactive power and prevent overvoltage at the Point of Common Coupling (PCC). Power quality for PV systems is enhanced by integrating battery storage with the DC link of the PV energy conversion system [18, 19].

However, to address the limitations of battery storage, a hybrid energy storage system combining batteries and super capacitors is proposed for smoothing power fluctuations in solar energy integrated systems. This approach leverages the high energy density of batteries and the high-power density of super capacitors. By deploying a two-level power reference signal distribution technique along with self-adaptive wavelet packet decomposition, this system lessens the fluctuations in grid power that are brought about by variations in PV speed. Even though the super capacitor and battery parameters were chosen based on the study's experience, power quality can still be enhanced by economic optimization [20].

By charging and discharging the High-Temperature Superconducting (HTS) coil in accordance with the PV array output and utility electricity quality, Superconducting Magnetic Energy Storage (SMES) improves the power quality of PV and Distributed Face-Green (DFIG) systems. Although power quality has been enhanced, the SMES coil's high current flow might make its deployment more difficult in practice. To address this issue, better control techniques or parallel linking of multiple SMES units could be explored in future studies.

Various technologies, including electric springs, Dynamic Voltage Restorers (DVRs), and soft computing-based methods, are utilized to enhance the power quality of RE systems. For instance, a fuzzy logic-controlled DVR mitigates harmonics in a hybrid PV/DFIG system. It is important to note, though, that the voltage deviation at the Point of Common Coupling (PCC) and the harmonic content of voltage signals are not used as inputs to the fuzzy controller in this proposed method. It might be feasible to enhance harmonics even further by keeping these factors in mind [20, 21].

TABLE IV. TECHNIQUES THAT IMPROVE POWER QUALITY

Filters	Control	FACTS Devices	Energy Storages
Passive Filters	Adaptive Control	STATCOM	Battery
Active Power Filters	Sliding Mode Control	SVC	Shunt capacitor
Hybrid Filters	Comprehensive Control	TCSC	Flywheel Energy Storage

A. *Shunt Capacitors*

In a power distribution system, an electrical engineer installs a connector parallel to the transmission. This gadget is known as a shunt capacitor. Power factors, low voltage regulation, and poor reliability are just a few of the power transmission problems that the shunt capacitor lessens. It is further separated into LV and HV capacitors.

B. *Connection of The Shunt Capacitor*

This study minimizes energy-dissipated losses during electrical power supply by presenting an ideal methodology based on the use of shunt capacitors to mitigate the effects of increasing renewable energy penetration. It incorporates a method of cooperative learning that makes use of the best possible answer in order to enhance search skills. There are two distinct scenarios looked into. To reduce power losses, the recommended approach is first applied with only the shunt capacitors taken into account, attached in multiple locations. Nonetheless, capacitors are primarily used in three applications:

- Electric pole-mounted capacitors: Usually, these are installed on electric poles as fixed or movable units. The typical range of capacitor units mounted on poles is 300–3000 kVAR; these variations are helpful for power loads that fall between 460 and 33 kV.
- EHV shunt capacitor banks: High voltage substations supply power to load centers in large quantities. Transmitting power loads at high points usually results in significant voltage drops on these lines. Therefore, anytime reactive power is needed, the EHV capacitors are used.
- Capacitor banks are installed in substations to function at voltages ranging from 2.4 to 765 kV. The parties involved carefully inspect the load flow and stability of the banks before installation.

In addition to these places, additional locations for capacitors are also used as needed. The star connection and the delta connection are the two most common methods of connection. Moreover, the cords' interchangeable points are connected to one another. There is a neutral or star point on the connection, and the line and phase currents are the same. This connection is mostly used in transmission networks and can receive up to 230 V from each curve. Even better, power distribution networks usually use this connection more frequently because each series can receive a maximum of 414 V. Because of this, this connection requires a lot of insulation to shield it from the harmful effects of high-power voltages.

C. Voltage Level Enhancement with the use of Shunt Capacitors

The impact of shunt capacitors (Voltage at bus 8) (line fault from line 7 to 8) can be seen in Figure 3 and the Voltage drop after adding capacitors in 57% pv energy can be seen in Table V.

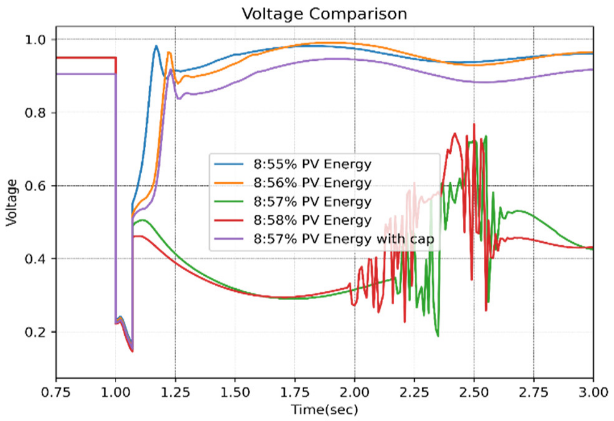

Fig. 3. Voltage comparison at Bus 8.

TABLE V. VOLTAGE DROP BETWEEN 55% TO 58% AND 57% WITH CAPACITORS

PV energy	Voltage drop	status
55%	0.1637423038482666	stable
56%	0.15722447633743286	stable
57%	0.12031149864196777	unstable
58%	0.11727101355791092	unstable
57% with cap	0.15372972190380096	stable

A comparison of the voltage drop in the system with and without shunt capacitors (Voltage at bus 8) (line fault from line 7 to 8) is shown in Figure 4.

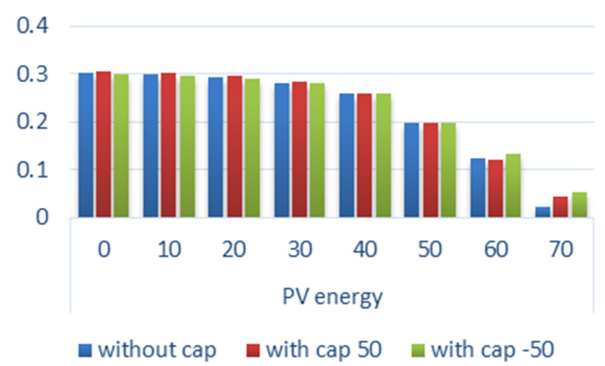

Fig. 4. Voltage drop in the system with and without shunt capacitors.

The Integrating PV units with capacitor banks resulted in a major reduction in grid power supply and a significant reduction in CO_2 emissions, even though the emissions were not considered as a mathematical objective. Thus, in subsequent work, it is advised that this is formulated as an additional objective function or constraint.

IV. CONCLUSION

The grid's integration of high concentrations of Renewable Energy Sources (RES) presents a number of challenges, including low inertia, reduced power quality, and high levels of uncertainty. In addition to outlining the main obstacles and possibilities related to RES grid integration, this paper also emphasizes the impact of the growing RES penetration on the power system grid. The increased use of renewable energy has a detrimental effect on the system's harmonics and oscillations. The need for techniques to improve power quality, like energy systems and adaptive control, is emphasized. Power system planning and operation are benefited greatly from power flow analysis, also known as load flow analysis. An overview of the power flow problem, its formulation, and different approaches to solving it are provided in this study. A power system's power flow model must be constructed using pertinent network, load, and generation data.

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