

REACTIVE POWER COMPENSATION USING FUZZY GAIN SCHEDULING CONTROLLED STATCOM FOR GRID CONNECTED PV SYSTEM

R. Ganesh ,

Assistant Executive Engineer R&D TANGEDCO, Chennai- 60002, India
Tel: +91 9444772068, krgganeshtneb@gmail.com

Dr. V. Senthil Kumar

Associate Professor, Department of Electrical and Electronics Engineering, College of Engineering
Anna University, Chennai, India Tel: +91 9444100661, sensang@annauniv.edu

Abstract: *Integration of a grid-connected renewable energy system is expected to meet the energy demand of the grid and reduce the carbon emission thereby global warming. This paper presents a grid-connected photovoltaic (PV) system combined with STATic synchronous COMPensator (STATCOM) that uses Fuzzy Gain Scheduling controller, to improve the grid quality of the power system by reactive power injection from STATCOM to compensate the voltage oscillation and to improve the voltage stability. This paper compares the proposed STATCOM with Fuzzy Gain Scheduling (FGS) controller for the dynamic state voltage oscillation of the PV system with the conventional PI controller for voltage compensation. On testing the proposed system through simulation using MATLAB/Simulink, the proposed model was found to be effective in mitigating voltage sags and swells with improved voltage regulation and power factor.*

Keywords: *Photo Voltaic (PV) system, STATCOM, Reactive power compensation, Incremental conductance (IC), Maximum Power Point Tracking (MPPT), Balanced/Unbalanced load, PI controller, Fuzzy gain scheduling (FGS).*

1. INTRODUCTION

Fossil fuel though plays a significant role in energy generation, results in increased gas emission, especially carbon dioxide and methane. To reduce pollution, the utilization of renewable energy is being considered for energy generation in the recent decades [1]. Further, increase in global warming and the depletion of fossil fuel reserves has made many to seek sustainable energy solutions. Apart from the hydropower, the wind and the photovoltaic energy are the most promising for meeting the energy needs. On its own, the wind energy is capable of supplying large amounts of power, but its presence is extremely different. The technical and functional characteristics of wind-diesel hybrid systems have various disadvantages like limitation of power generation in remote areas only and the high price for the complicated and complex mechanism of gears.

The other vital renewable energy is the solar energy which is available throughout the daytime. It has many advantages as mentioned earlier like less maintenance, no wear and tear, etc. Primarily PV systems are used as stand-alone systems for pumping water, lighting domestic and street lights, running electric vehicles, military and space applications and utility grid-connected systems.

PV systems are usually designed to operate near the unity power factor to utilize the solar energy fully. In this case, the PV system injects active power into the utility grid, which may change the reactive power flow of the system. The lack of reactive power increases the voltages of nearby buses. On the contrary, the over-voltage produced by the PV system adversely affect the performance of its utilization. Power fluctuation may cause power swings in lines, over- and under-loadings, unacceptable voltage fluctuations and voltage flickers [2].

The primary STATCOM model consists of a step-down transformer with leakage reactance X_T , a three-phase Voltage Source Inverter, and a DC capacitor. The AC voltage difference across this transformer leakage reactance produces reactive power exchange between the STATCOM and the power system at the point of interface. The voltage at the point of interface can be regulated to improve the voltage profile of the interconnected power system, which is the primary function of the STATCOM. A secondary damping function can be added to the STATCOM for enhancing the power system dynamic stability [20]. The function of the STATCOM is to regulate the bus voltage by dynamically absorbing or generating reactive power to the network, like a thyristor static compensator.

Several researchers have investigated the balanced grid faults and found that the majority of grid faults arises due to its unstable nature. The unbalanced voltage can cause unbalanced loading of equipment connected in the system and increase the overall line losses. The STATCOM control structure can adapt to these unbalanced voltage conditions [3], and the positive and the negative sequence of the voltage can be controlled

independently. The STATCOM can inject either a positive-sequence current or a negative-sequence current [5]. Different current injection methods based on symmetrical components can also be given to the STATCOM, [4], [5] resulting in different outputs of power distribution. This paper proposes the integration of STATCOM with the grid-connected PV system for voltage control. Again it leads to all drawbacks by the PI controller in the STATCOM system too. Hence, this paper proposes the STATCOM via Fuzzy Gain Scheduling (FGS), controller for the voltage compensation. Many theoretical and industrial applications have been reported for fuzzy logic control [18] [19]. Furthermore, FGS is proposed for voltage compensation to enhance the voltage stability. A block diagram of the proposed system is shown in Fig. 1.

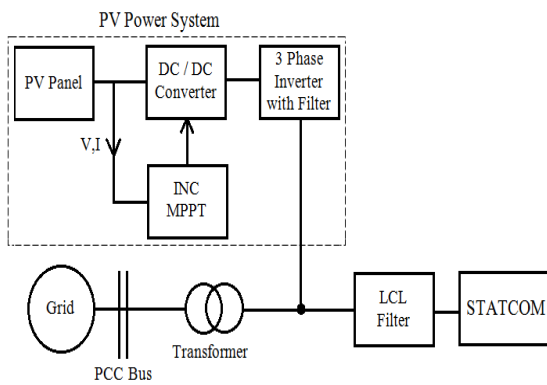


Figure 1. Block diagram of the proposed system

The proposed system consists of PV power system, LC filter and STATCOM connected with the grid. The system is analyzed using MATLAB simulation analysis. In this paper, the PV system is described in section 2, STATCOM is discussed in section 3 and simulation analysis and results are discussed in section 4.

2. PV POWER SYSTEM

The PV power system consists of the PV panel, MPPT algorithm, DC-DC buck-boost converter and three-phase inverter with filter. The PV panel output voltage is varied according to the change in solar irradiation. The DC-DC converter with MPPT delivers a constant DC voltage as briefly discussed in section 2.2. The controlled DC voltage is converted into three-phase AC with the help of a three-phase inverter, and the output filter along with the inverter produces a pure sinusoidal output.

2.1 PV Panel

The solar panels are mainly made of semiconductor materials, among which silicon is the most abundantly used. It generates DC power when subjected to irradiation. Working of a PV cell is similar to a PN junction fabricated in a thin wafer or layer of semiconductor, where there are diffusion currents and drift currents for the direct and reverse polarization, respectively. The cells function in the opposite direction to achieve the expected movement of current. When the

PN junction is exposed to light, the photons with energy greater than the gap of energy are absorbed, making the emergence of electron-hole pairs. These carriers are separated under the influence of electric fields within the junction, producing a current that is relative to the incidence of solar irradiation [6]. However, the power thus generated through a single PV cell is insignificant. To overcome the power challenge, many PV cells are interconnected, where the number of cells in series decide the voltage obtained and the number of cells in parallel decide the amount of current produced [7].

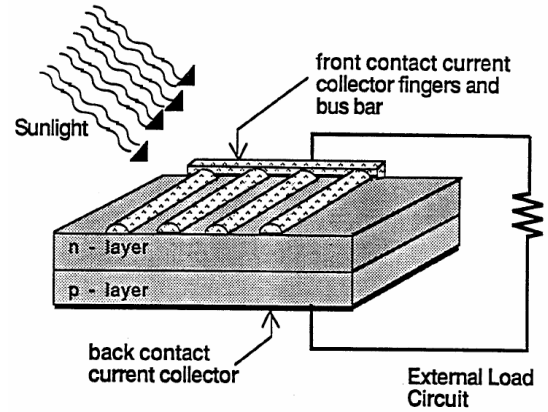


Figure 2. Equivalent circuit of solar panel

The following parameters were applied in the computation of the net current of a PV cell.

$$I_L = \left(\frac{\Phi}{\Phi_{REF}} \right) \times \left(I_{L,REF} + \mu_{ISC} \times (T_C - T_{C,REF}) \right) \quad (1)$$

where,

Φ, Φ_{REF} = irradiance at the new and reference conditions, W/m².

$I_{L,REF}$ = light current, in amps, at the reference condition.

μ_{ISC} = Manufacturer-supplied temperature coefficient of short-circuit current in amps per degree.

(As will be shown later, the short-circuit current is nearly identical to the light current. For practical purposes, the terms are interchangeably used).

$T_C, T_{C,REF}$ = cell temperature at the new and reference conditions.

2.2 DC-DC Buck-Boost Converter

Buck-boost converter is a step-up/down converter which could be connected between any renewable energy source/battery and load. It is derived from the combination of buck and boost converter. The converter preceded by boost and followed by buck is also a step-up/down converter. To achieve step-up/down voltage with the minimum components, a buck-boost converter is considered as the optimum converter, in which it is preceded by a buck and followed by a boost converter.

The buck-boost converter is designed with two semiconductor switches such as a diode and a transistor, and two energy storage elements, namely a capacitor and

an inductor. The switch may be of MOSFET or IGBT or BJT; however, in this paper MOSFET is proposed. Fig. 3 shows the circuit of a buck-boost converter.

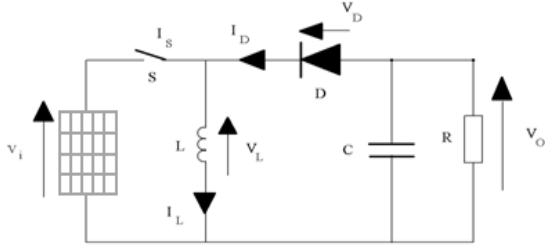


Figure. 3. Schematic of a buck-boost converter

A wide range of duty ratio (D) in the buck-boost converter provides the voltage control of the PV panel from open circuit voltage to short-circuit current. The Perturb and Observe (P&O) and Incremental Conductance (InC) are the widely used Maximum Power Point Tracking (MPPT) algorithms, but the disadvantage of the P&O method is that it is unable to track the peak power under fast varying atmospheric conditions is overcome by the IC method. The InC algorithm is proposed in this paper.

The InC algorithm states that the solar array will operate at the maximum power point [8] when the rate of change in output conductance is equal to the negative output conductance. Therefore, an InC algorithm is proposed for MPPT in this paper. It decides the duty ratio of DC-DC converter connected after the PV panel based on the power deviation. InC MPPT varies the voltage gain of buck-boost converter by varying the duty ratio with respect to the change in input voltage effect of irradiation. Thus, it maintains a constant voltage at the end of the DC-DC converter.

3. Introduction to Static Synchronous Compensators

With the advent of Voltage Source Converter (VSC) technology built upon self commutating controllable solid-state switches, a new family of FACTS controller such as (STATCOM) has been developed. The self commutating VSC, called as DC-to-AC converter, is the backbone of these controllers which are employed to regulate reactive current by the generation and absorption of controllable reactive power with various solid-state switching techniques [22].

The STATCOM is a shunt-connected reactive compensation equipment which is capable of generating and/or absorbing reactive power whose output can be varied so as to maintain the control of specific parameters of the electric power system. STATCOM is defined by IEEE as "a self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase voltage, which may be coupled to an AC power system for the purpose of exchanging independently controllable real and reactive power".

Active power flow is determined by the phase angle difference among the sources, while reactive power flow

is determined by the voltage magnitude difference among the sources. Hence, STATCOM can control the reactive power flow by changing the fundamental component of the converter voltage with respect to the AC bus bar voltage both phase wise and magnitude wise.

3.1 Control Structure of STATCOM

Voltage oriented vector control with grid voltage is the basic control principle of STATCOM [3]. It is the combination of two control structures, such as inner current controllers and outer DC voltage and reactive power controllers. The control structure is adopted in four steps to guarantee safe operation and to achieve the given current injection targets under unbalanced grid voltage condition. The four steps are

1. Positive and negative-sequence detection based on Dual Second-Order Generalized Integrators (DSOGI).
2. Current injection target calculation based on the power calculations under unbalanced grid voltage.
3. Negative-sequence current control using resonant controllers.
4. DC voltage and reactive current control loop modifications.

The overall control structure [23] is shown in Fig. 4.

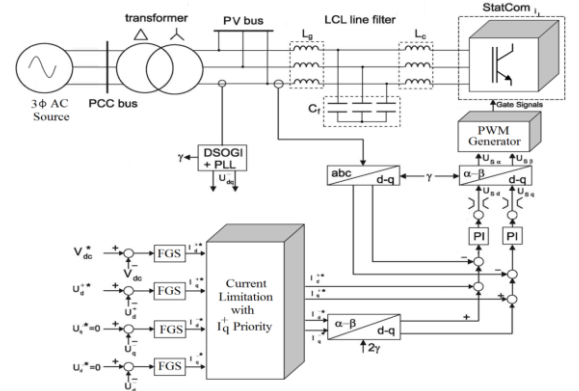


Figure.4. The proposed control structure of the STATCOM to control the positive-and the negative-sequence voltage independently

FGS controller is proposed for the voltage controller that has a rotating dq reference frame with grid voltage orientation in STATCOM.

The inner current loop is designed with a PI controller for negative-sequence and positive-sequence current in STATCOM [4], [10]. The PI controller equation is

$$U(s) = K_p e(s) + \int K_i e(s).ds \quad (2)$$

The number of levels of VSC in the STATCOM is chosen based on the power rating. Nominal-power applications are employed with a two-level VSC, while multilevel topologies are used for high-power applications. Since IGBTs are used in the converter, the output voltage is non-sinusoidal; hence, the LCL filter in

sequence with the converter is proposed in this article to filter ripples and produce pure sine wave from the inverter output.

The outer voltage control loops are designed to control the DC voltage and the AC voltage. The AC voltage is at the connection point of the STATCOM and is separated as positive and negative-sequence voltage. Using the sequence separation, the positive and the negative sequence of the voltage appear as DC values and is processed by the FGS controllers to produce reference currents. It states the separation of the measured voltage into positive- and negative-sequence components which decides the accuracy of the reference current and voltage compensation. There are many sequence extraction methods [12], [13]; however, the dual second-order generalized integrator [11] is proposed in this paper. The current references given by the four outer controllers are limited to the maximum STATCOM current for a safe operation.

The positive and negative sequence current references are added to produce reference signals to the inner current loop. The negative sequence current references must be transformed into the positive rotating reference frame by a coordinate transformation with twice the grid voltage angle [14].

To ensure a safe operation of the STATCOM within its current capability, the current references given by the four outer controllers must be limited to the maximum STATCOM current. The priority is on the positive-sequence reactive current I_{q+} , when the grid voltage is unbalanced, i.e., (it contains a negative sequence, and the currents become unbalanced). According to Wang *et al.* [21], a small amount of negative-sequence voltage V_{s-} can lead to a high amount of negative-sequence currents I_{s-} , described by

$$I_{s,pu}^- = \frac{V_{s-}}{\omega_s \cdot \sigma \cdot L_s \cdot I_{s,N}} \quad (2)$$

The target of the first method is to compensate the positive-sequence voltage, while the negative-sequence voltage will remain unchanged. The target of the second method is to eliminate the negative sequence of the voltage, while the positive-sequence voltage will remain unchanged. Depending upon the voltage dip or fault, the method is selected for compensation.

In this paper, the balanced and the unbalanced load faults in the grid are compensated by using the positive-sequence voltage and the negative-sequence voltage compensation method using FGS is proposed.

The reference currents produced by the voltage controllers decides the voltage compensation. Conventional PI controllers are parameter dependant and works effectively in a steady state such as constant load. A transient state, such as sudden change in three phase or unbalanced load changes in three phase, causes poor response because tuning of controller gains are not varied with respect to sudden changes in voltage, therefore, it

consumes more time to compensate the voltage and reactive power. It necessitates the FGS for online tuning of k_p and k_i .

4. Fuzzy Gain Scheduling for Voltage Compensation

The fixed value of K_p and K_i in a PI controller produces the instability during a change in load. Online tuning of K_p and K_i in a PI controller can conquer this problem. The FGS controller fuzzy logic module is considered as an auto tuning module for parameters k_p and k_i in PI controller [15-17]. The FGS controller is considered as the major contribution in this research. The block diagram of the control system is shown in Fig. 5.

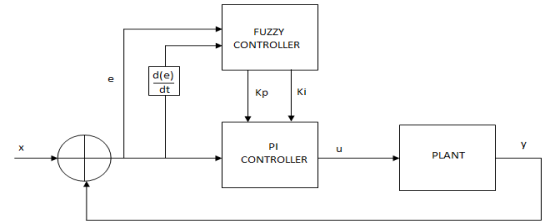


Figure. 5. Fuzzy Gain Scheduling Block Diagram

where, k_p is the proportional gain, k_i is the integral gain and $e(k)$ is the voltage error and control algorithm of PI as given in equation (4). The design algorithm of FGS in this paper adjusts the k_p and k_i parameters online through Fuzzy based on the current e and ec to make the control object attain the good dynamic and static performances [17]. This paper proposes four Mamdani FGS controllers for tuning voltages.

DC voltage and dq voltage of three-phase voltage error e and error change rate ec are used as fuzzy input and the proportional factor k_p the integral factor k_i are used as fuzzy outputs. The degree of truth of e and ec are configured as 5 degrees, all defined as {NL, NM, ZO, PM, PL}, where NL, NM, ZO, PM, and PL represent negative Large, negative medium, zero, positive medium and positive Large, respectively [18][19].

The degree of truth of k_p and k_i are configured as four degrees and are defined as {Z, S, M, L}, where Z, S, M and L represent zero, small, medium and Large. The membership functions of e , ec , k_p and k_i are triangular distribution functions. The membership functions for each variable are shown in Figs. 6-8, respectively.

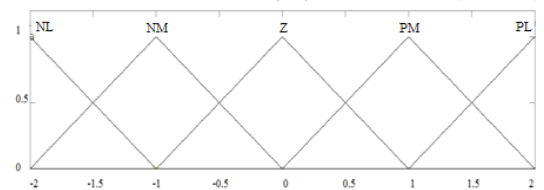
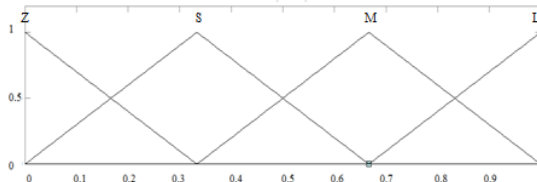
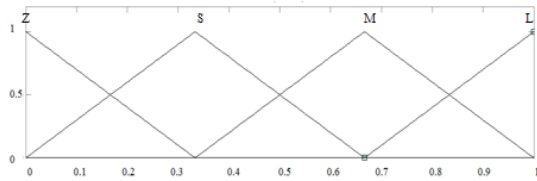


Figure. 6. Fuzzy Membership Functions of e and ec



The objective of designing fuzzy rules is that the output of the fuzzy can make the system output response dynamic and static performances optimal. The fuzzy rules are generalized as Tables 1 and 2 according to the experiment in induction motor drive system and simulation analysis of the system. The Mamdani inference method is used as the fuzzy inference mode, and k_p and k_i are written as 25 fuzzy condition statements. Based on the statements, the MIN - MAX method of fuzzification is adopted. The Centroid method is adopted for defuzzification. FGS controller reduces the change in voltage during load change.

$\begin{smallmatrix} ec \\ e \end{smallmatrix}$	NL	NM	ZO	PM	PL
NL	L	L	L	L	M
NM	M	L	M	M	M
ZO	M	L	Z	M	L
PM	M	M	M	M	M
PL	M	L	L	M	L

5. Simulation Results and Analysis

The STATCOM system was simulated with the grid-connected PV system. The STATCOM, which is modeled as controlled voltage sources, was connected between PV system and grid. All devices are connected to the same low voltage bus and then connected to the medium voltage bus by a transformer. The medium voltage level was then connected to the high voltage level by a second transformer. Both transformers were rated for the sum of the PV system and STATCOM power and had a series of impedance of 5% and 10% per unit. The fault was assumed at the high voltage level of the grid.

The entire system was simulated using MATLAB / Simulink. The performance of the PV system with STATCOM was analyzed with various loads in the grid. Sudden changes of the load in the grid created sag and swell in the grid voltage. In this paper, balanced and unbalanced loads were considered for analysis. The sudden rise in the load made sag in voltage while a sudden drop in load caused swelling in voltage. The simulation model of the proposed system is shown in Fig. 9.

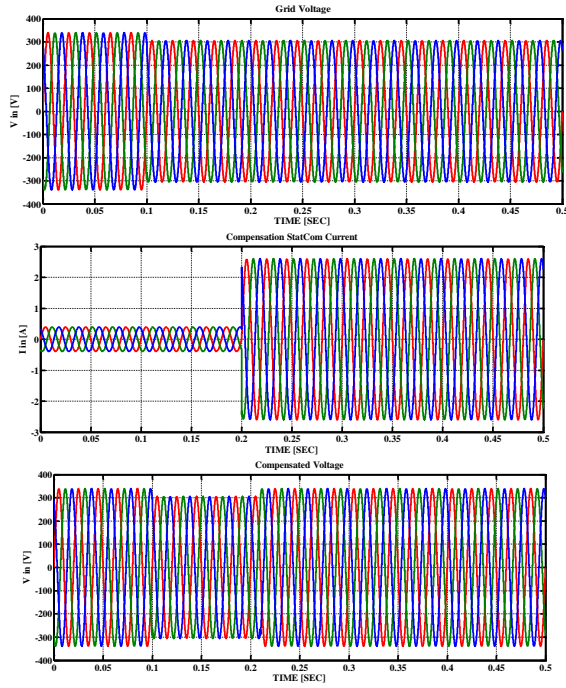


Figure 10. Sag compensation in voltage by balanced load change

Fig. 11 shows the swell caused by a sudden rise in load in three phases equally, compensation signal and compensated voltage.

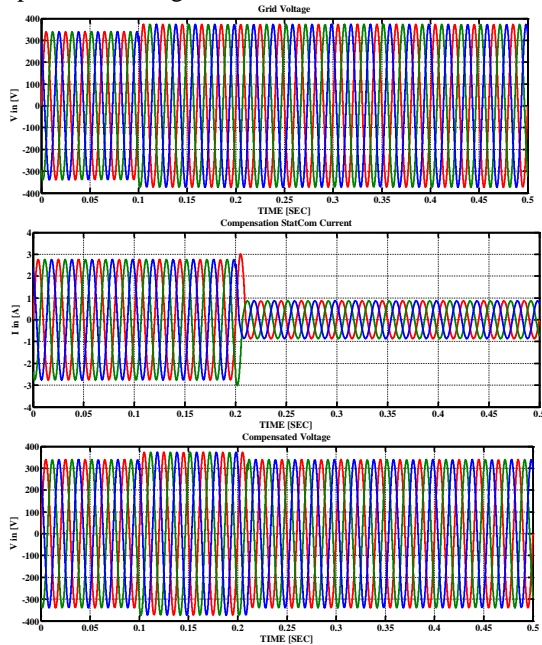


Figure 11. Swell in voltage by balanced load change

The analysis load was raised at 0.1 seconds in an unbalanced condition, while the STACOM was activated at 0.2 Seconds to reveal its performance Fig. 12 shows the compensation signal, compensated voltage and unbalanced sag caused by a sudden rise in load in three phases unequally.

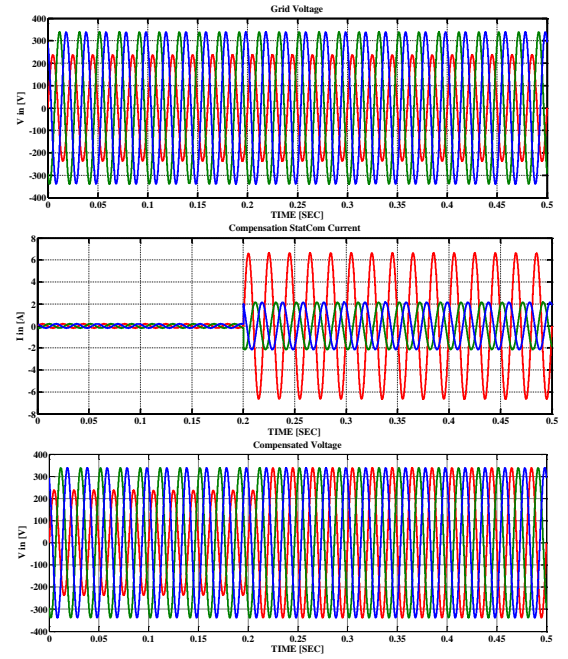


Figure 12. Sag in voltage by unbalanced load change

The figures, 10-12, it is evident that the grid voltage is oscillated by load fluctuation. Nevertheless, the reactive power current injection from STATCOM compensated the voltage oscillation and makes it stable.

6. Conclusion

The reactive power compensation and voltage stability of grid-connected PV system with the STATCOM using FGS controller were analyzed in this paper. The proposed reactive power compensation increased the voltage quality of PV power system. The performance of proposed system is measured with various parameters of grid disturbance, such as sag and swell, occurring under balanced and unbalanced load conditions. From this study, it is concluded that the FGS-based STATCOM could compensate the voltage oscillations and maintain power quality and mitigate the balanced and unbalanced voltage problems. Further the effective application of FGS-based STATCOM could increase the utilization of PV systems in the grid.

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