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Fuzzy Gain Scheduling Controlled Statcom for Grid Connected SPV System

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Abstract: Renewable energy power system connected to the grid reduces the gap between source and demand and also limits the carbon emission. When SPV system integrated with the grid, the main grid issues are power quality, voltage stability and reliability. The voltage dips, unbalanced voltage and negative sequence voltage creating power quality issues with the grid. Many research works are under development to get balanced grid voltage. By the introduction of STATCOM in grid-connected systems, this can be achieved. In this study, grid integrated SPV system analyzed for both the unbalanced and voltage fluctuation and fuzzy gain scheduling controller is proposed for voltage compensation in STATCOM to enhance voltage stability. The total system is examined by simulation using MATLAB/Simulink.

Key words: Solar Photo Voltaic (SPV) system, STATCOM, Incremental Conductance (IC), Maximum Power Point Tracking (MPPT), balanced/unbalanced load, PI controller, fuzzy gain scheduling introduction

INTRODUCTION

In recent years, the natural asset from the earth has been deteriorated heavily and our living environment harshly contaminated (Ankaiah and Nageswararao, 2013). Many research works are being carried out throughout the globe to preserve fossil fuel and save the earth for future generation. With the aggregate worry of global warming and the fatigue of fossil fuel reserves, many are seeing at sustainable energy solutions to preserve the earth for the future generations. Apart from the hydropower, the wind and photovoltaic energy grips the most possible to meet our energy demands. The renewable wind energy is capable of supplying massive quantity of power but its occurrence is highly unpredictable. The technical and operational features of hybrid systems are various disadvantages like power generation only in remote areas, the high cost for its complex. Solar energy is the other important renewable source and which is available in the earth all over the day period.

Solar photovoltaic having more advantages like easy installation, low maintenance cost, no mechanical movements The SPV power system are of two types one standalone and another one is grid connected system. The standalone systems used for domestic, street lighting, agriculture irrigation system and defense and space research applications. The grid-connected systems used for bridging the demand and supply of power system. Even though SPV power system has its advantages, it has disadvantages during the occurrence of fault the solar plant island from the grid. Since, SPV power plants continue to supply the power to the load even after when the grid is not available in the power network, this lead to safety hazard to the working personal. Mainly the SPV power plant considered to be operated at UPF. Hence, it requires reactive power from the grid for its stable operation.

Because of the reactive power requirement from the grid that leads to rising in voltage in the utility bus. Moreover, this over voltage produced due to SPV power system develops more difficulty for both utility and on consumer sides. The difficulties are power swings, overloading, voltage flickers and voltage fluctuations (Eltawil and Zhao, 2010).

Literature survey was carried out on grid faults and reveals that the grid failures are of unbalance in nature. The unbalanced nature is due to rise in voltage and overloading. The unbalanced voltage can produce unbalanced loading of equipment connected to the system and the overall line losses are increasing. The STATCOM used with control structure to these unbalanced- voltage conditions (Hochgraf and Lasseter, 1998) and the (+) and the (-) voltage sequence operated independently. The STATCOM can inject a (+) sequence current or it can also inject a (-) sequence current as required by the system (Rodriguez *et al*., 2010). Different types of current injection based on symmetrical

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components of voltage can be given to the STATCOM, subsequently different output power are delivered (Rodriguez *et al.*, 2010). This study proposes the integration of STATCOM with the grid-connected PV system for voltage control. Again it goes to all drawbacks by the PI controller in the STATCOM system too. In this study, an STATCOM via Fuzzy Gain Scheduling (FGS) controller is proposed for the voltage compensation. The fuzzy logic control become an active and fruitful research area with many theoretical works and industrial applications being reported (Neema et al., 2011; Zadeh, 1965). Hence, FGS is proposed in this study for voltage compensation to enhance voltage stability.

MATERIALS AND METHODS

SPV power system: The SPV modules are of usually three types they are monocrystalline, polycrystalline and thin films. Moreover, modules are nothing but semiconductor devices made up silicon crystals. Electric power is produced in the modules when they exposed to solar irradiation (Fig. 1).

Moreover, the electrical energy generator by these modules is of DC in nature. The principle of SPV cells is similar to that PN junction semiconductor. In solar cells, the function is of reverse in nature. When the PN junction of the sole cell exposed to solar light, the photons absorbed and emitted electron-hole pairs.

These carriers separated under the guidance of electric fields within the junction, producing a current specifically about the incidence of solar irradiation (Kumari and Babu, 2012). Electric power generated from the SPV cell is small. In the scale of SPV system, these SPV cells are linked in such a way that the cells in series depend on the voltage of the module and of cells in parallel decide the current (Petreus *et al.*, 2008). The following were the parameters used to compute total current supplied by a PV cell Eq. 1:

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

Where:

Φ, Φ_{REF} = Irradiance at the reference conditions (W/m^2)

$I_{L,REF}$ = Light current (amps)

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

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

Incremental conductance method: The MPPT (Maximum power point tracking) is important for SPV system because of its variable power nature and fluctuation

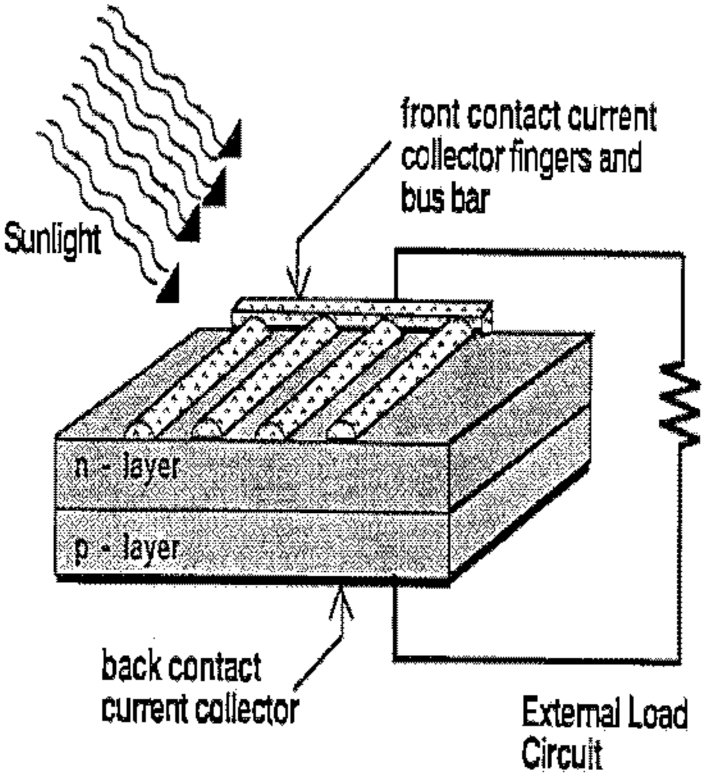

Fig. 1: Equivalent circuit of solar panel

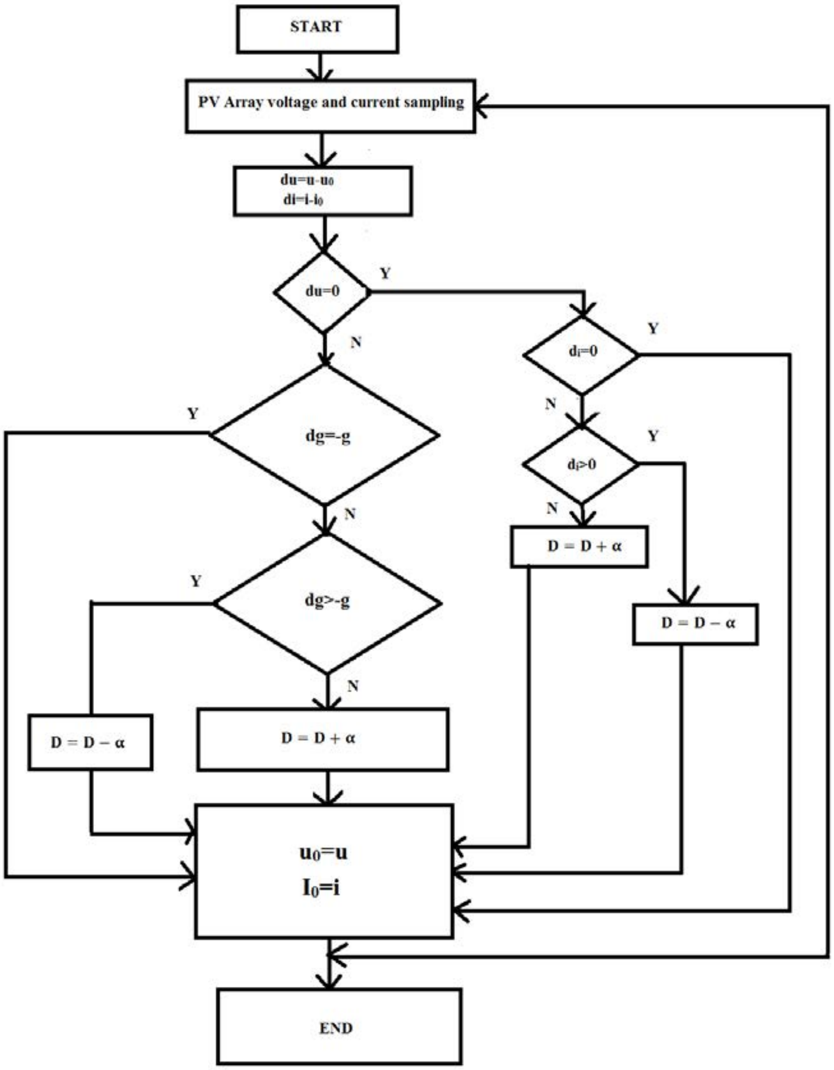

Fig. 2: Incremental conductance MPPT flowchart

voltage nature throughout the day. The ICM constructed on the principle that the derived of the SPV array power curve is zero at Maximum Power Point (MPP). In this method, the PV model operates at maximum power when the Voltage reference V_{ref} reached.

When there is a change in irradiation or the temperature of the solar, then the current I changes and the MPP be changed. The proposed algorithm decreases or increases the duty cycle and tracks the fresh MPP again. A fast calculation of the slope is required and the sampling rates should be high for obtaining a better result.

This technique requires a suitable value of the increment size. The MPP may be tracked quickly with bigger increments but the system might fluctuate about the MPP. Figure 2 represents the algorithm for the incremental conductance. The algorithm starts by computing the input voltage and current of the SPV. Then, it calculates the difference from the previous measurement and determines the power. The different current and voltage needs to perform at each step. The equations of this method are as follows Eq. 2 and 3.

$$dI/dV = dg \tag{2}$$

$$i/u = g \tag{3}$$

The current I and voltage V are SPV module outputs. The equations represent the both SPV module incremental conductance and the instantaneous conductance. The percentage change in conductance is less then output conductance, the solar array function at the maximum

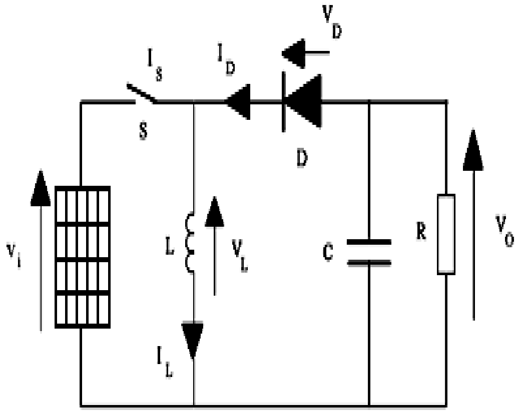

Fig. 3: Schematic of buck-boost converter

power point (Hoffmann *et al.*, 2011). By introducing incremental conductance algorithm, the maximum power delivered is above 98% and this method is easy to implement.

DC-DC buck-boost converter: The boost converter is widely used to locate the crucial point of power of the SPV array. It is a simple circuit with good response speed. Any algorithm of MPP is flexible to implement with software and hardware. The boost converter can operate in continuous conduction mode along with discontinuous conduction mode. The mode of conduction depends on the capacity for storage of energy along with the relative time frame of the switching. The output voltage is dependent upon the duty cycle; it adjusted by the maximum power controller.

The buck converter used in the same technique as the boost converter. The change is the link in terms of the output and input voltage. The buck employed in reducing the output voltage. Since the voltage, of the SPV array, changes continuously with temperature and irradiation, the duty cycle still changes continuously to track the highest probable power point of the SPV. The Buck-Boost converter is the mixture of the buck converter and the boost converter.

The Buck-Boost converter designed with at least two semiconductor switches such as the diode and a transistor and the storage element, a capacitor and an inductor. In this paper, MOSFET is proposed for semiconductor switches. Figure 3 shows the circuit of buck-boost converter. Buck-Boost converter is used to obtain the MPPT of the grid-connected SPV power system.

The buck-boost is a simple converter with upright reaction rapidity and the regulatory method is flexible. The overall efficacy of the photovoltaic with buck-boost is improved. . The output-input voltage conversion ratio is the conversion ratio of the two converters has the same duty cycle.

Buck-Boost conversion ratio achieved in the initial stage. Buck-boost converter thus does not have a non-operational zone that is no limitation for duty ratio. By altering the duty cycle operation from short-circuits current to open-circuit voltage of PV panel.

Control structure for STATCOM: Mainly STATCOM can be employed to regulate voltage, power factor control and steady power flow. Normally, STATCOM is the voltage source inverter employ a combination of thyristor controlled reactance with fixed or variable capacitance. The principal of operation of STATCOM is voltage source vector controller (Hoffmann *et al.*, 2011). The two type of control structures employed in the proposed STATCOM. The main objective of this control is to improve voltage regulation. They are the inner current controller and outer voltage and reactive controller.

These control structure employed in 4 steps for the safe security operation and they described as follows. First step the detection of (+) and (-) sequence components employed on dual second order generalized integrator's (DSOGI). Second step current injection target control found in the power calculations under unbalanced grid voltage conditions.

The third step (-) sequence current control adopted resonant controllers. Fourth step adjustments of DC voltage and reactive current control loop. The SPV solar modules are bundled and represented SPV bus that integrated with the grid by proposed inverter with STATCOM. The LCL line filter used to reduce the harmonics developed in the inverter circuit. A transformer is used to tie the SPV inverter and grid.

The current injection of STATCOM divided into two components that are active Ia and reactive Ir. For the inner current control structure, Proportional Integral (PI) is employed and for outer voltage control rotating dq reference with source voltage direction is proposed for the STATCOM. The PI controller limits are changed using the method proposed (Fig. 4).

The Ssimulation and PI controller gain design for three-phase converter described in Sahu *et al.* (2010) and Tripura and Babu (2011). The PI controller intended for negative current sequence and the positive current sequence in STATCOM.

$$U(s) = K_p e(s) + \int K_i e(s) ds \tag{4}$$

The many levels of VSC in the STATCOM are designed based on the power rating. Small power, applications are engaged with two-level VSC while

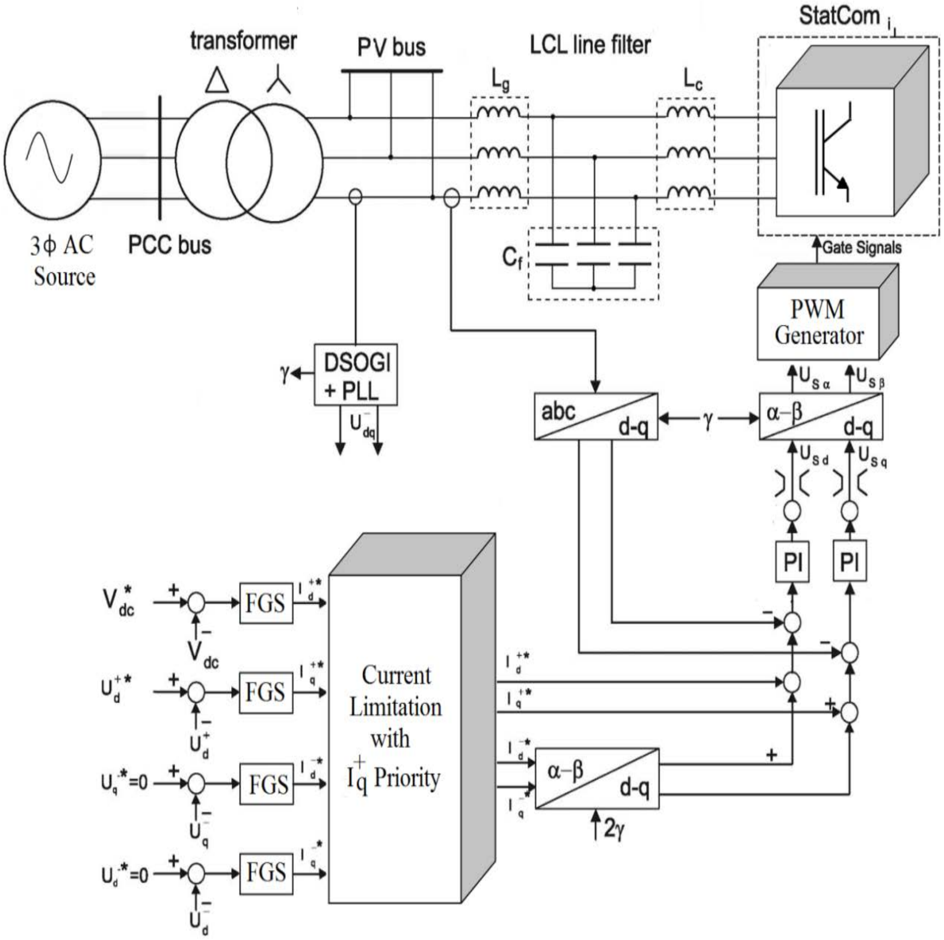

Fig. 4: The control structure of the STATCOM controls the positive and the negative-sequence voltage independently

multi-level VSC employed for high-power applications. IGBTs tuned in such a way that it remove ripples and produce clean sine wave from inverter output. The outer voltage control loops are planned to control both DC and AC voltage.

The STATCOM connection point AC voltage separated from (+) sequence and (-) sequence components. With these separations, the (+) and the (-) sequence of the voltage look as DC values and it is handled by PI controllers to produce reference currents. The importance of separation and DCOGI proposed in this study resolves the accuracy of reference power compensation.

The importance is on the (+) sequence reactive current. The reference signals for the inner current loop are produced by the (+) and (-) sequence current references. With the coordinate transformation and grid side voltage angle, the (-) sequence current is transformed into the positive rotating reference frame. In this study, the balanced and unbalanced faults in the grid are compensated using (+) sequence voltage and the (-) sequence voltage compensation method.

Fuzzy gain scheduling for voltage compensation: The fixed value of K_p and K_i in a PI controller produces the instability of a change in load. Tuning of Kp and Ki in PI controller conquer this problem. It necessitates the fuzzy gain scheduling for online tuning of K_p and K_i.

The Fuzzy Gain Scheduling (FGS) controller fuzzy logic module considered as an autotuning module for parameters Kp and Ki in PI controller (Tripura and Babu, 2011; Mokrani and Abdessemed, 2003). The fuzzy gain scheduling controller found to be the contribution to this research. The control system diagram is shown in Fig. 5. The control algorithm of traditional PI controller described in Eq. 5:

$$U(k) = k_p\, e(k) + k_i \int e(k) \tag{5}$$

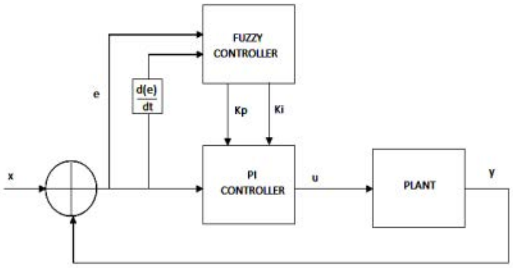

Fig. 5: Fuzzy gain scheduling

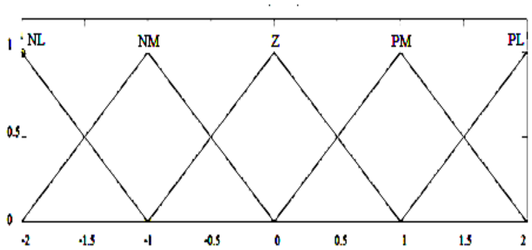

Fig. 6: Fuzzy membership functions of e and ec

Where:

k_p = The proportional gain
k_i = The integral gain
e (k) = The voltage error

In this study, fuzzy gain scheduling to adjust the k_p and k_i parameters online via fuzzy based inference on the current e and ec to make the control object attain the dynamic and static performances. This study proposes four Mamdani FGS controllers for tuning voltages.

The 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 kp the integral factor ki 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 (Neema *et al*., 2011; Zadeh, 1965).

The degree of truth of k_p and k_i are configured as 4 degrees 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, kp and ki are triangular distribution functions. The membership functions for each variable are shown in Fig. 6-8, respectively.

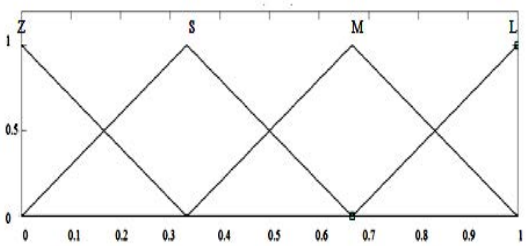

Fig. 7: Fuzzy membership functions of kp

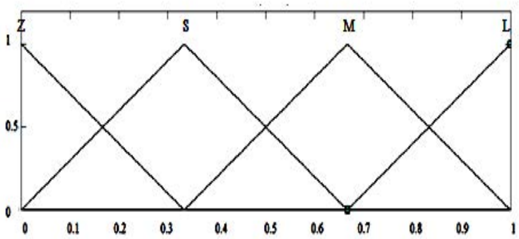

Fig. 8: Fuzzy membership functions of ki

Table 1: The control rules for Kp

e/ec	NL	NM	ZO	PM	PL
NL	Z	Z	Z	Z	Z
NM	M	M	M	M	M
ZO	L	L	Z	L	L
PM	M	M	M	M	M
PL	Z	M	L	L	L

Table 2: The control rules for Ki

e/ec	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

The designing of fuzzy rules is that the output of controller makesthe system output response dynamic and static performances optimal. The fuzzy rules are generalized as Table 1 and 2 according to the expert experiment in induction motor drive system and simulation analysis of the system. The Mamdani inference method is used as the fuzzy inference mode. Kp and Ki are written as 25 fuzzy condition statements. The MIN-MAX method of fuzzification is applied. The centroid method is adopted for defuzzification. Fuzzy gain scheduling controller reduces the change in voltage during load change.

RESULTS AND DISCUSSION

The system studied in a simulated model of 1MW SPV power system connected to the grid. The STATCOM interconnected between SPV system and grid. The STATCOM modeled as controlled voltage sources. Both devices connected to the same voltage side and then connected to the medium voltage bus by a step up transformer.

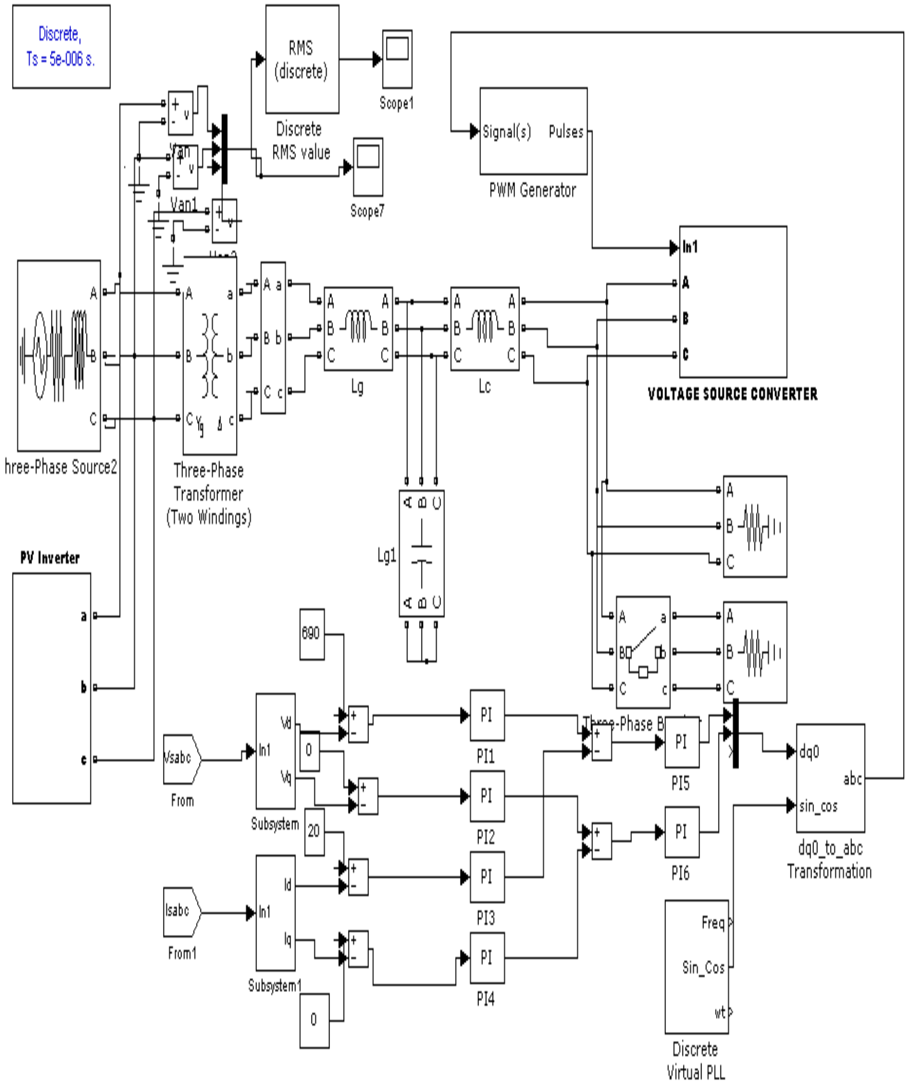

Fig. 9: The simulation model of the system

The rating of the transformer is for the total power requirement of the SPV system and STATCOM and has a series impedance of 5 and 10% per unit. The grid fault occurs at the high voltage level. The system is simulated using Matlab/Simulink. The performance of the SPV system with STATCOM is analyzed with various loads in the grid when sudden changes of the load are created sag and swell in the grid voltage. In this study, balanced and unbalanced loads are considered for analysis. The unexpected rise in the load makes sag in voltage whereas a sudden drop in load causes swelling in voltage (Table 3 and Fig. 9).

The system is initial with sag by the balanced and unbalanced load (Fig. 10). Figure 11 shows the sag caused by a sudden rise in load in three phases equally. Table 4 shows that the uncompensated sag in three phase voltage. All phase voltages are suddenly reduced (sag) equally because of the balanced load. Figure 11 shows the sag caused by a sudden rise in load in three phases unequally.

Table 3: Simulated system parameters

Parameters	Values
Input resistance	0.7
Input inductance	0.2 mH
Step frequency	10 kHz
Sample frequency	30 kHz
Input frequency	50 Hz
Max (Vl-l)	650 V

Table 4: Different types of voltage sag and swell

Type 1	Type 2	Type 3	Type 4	Type 4
200/0°	400/0°	265/0°	361/0°	241/0°
200/-120°	400/-120°	265/-140°	361/-106°	241/-134°
200 /120^0	400/120^0	265/140°	361 /106°	241/134°

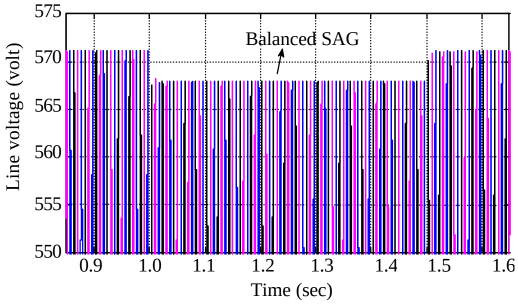

Fig. 10: Sag in voltage by balanced load change

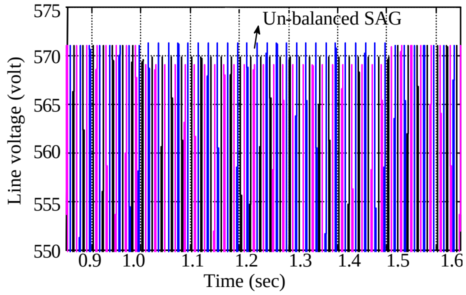

Fig. 11: Sag in voltage by unbalanced load change

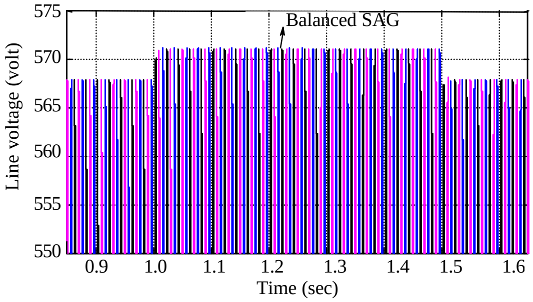

Fig. 12: Swell in voltage by balanced load change

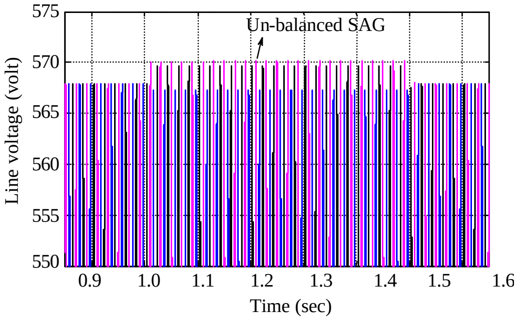

Fig. 13: Swell in voltage by unbalanced load change

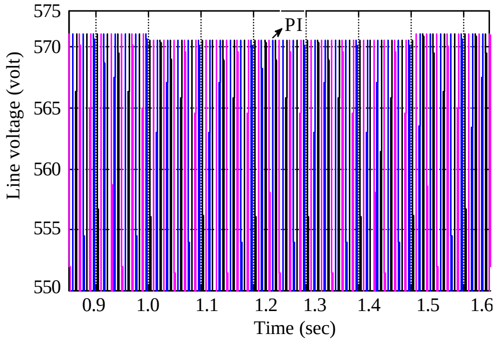

Fig. 14: Compensated voltage by PI controlled STATCOM

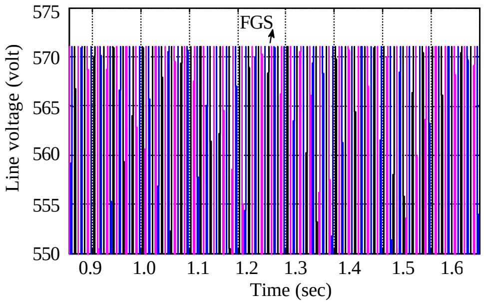

Fig. 15: Compensated voltage by FGS controlled STATCOM

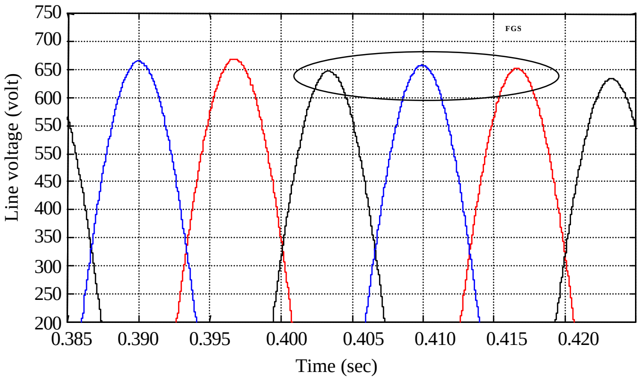

Fig. 16: Compensated voltage by FGS controlled STATCOM

Figure 12 shows that the uncompensated swell in three phase voltage that is all phase voltages are suddenly raised (swell) equally because of the balanced load. Figure 13 shows the effect of a sudden drop of an unbalanced load in grid voltage (swell) in three phases unequally. Figure 14 shows that the compensated voltage by the STATCOM for all above cases discussed.

Figure 15 and 16 shows that the compensated voltage by FGS controlled STATCOM for all above cases discussed.

CONCLUSION

Renewable energy source conservation is important than the generation. Voltage instability in a grid-connected SPV system reduces the efficiency of SPV system and power quality. To overcome this problem integration of grid-connected SPV system with the STATCOM is analyzed in this study. The performance of STATCOM analyzed with various grid parameters such as sag, swell, balanced and unbalanced voltages. From the simulation results that the STATCOM effectively compensates the oscillations in voltage and maintains power quality. The FGS-based STATCOM compensates well compare to the PI controller. The use of STATCOM effectively increases the efficiency of SPV systems in the grid. This proposed system may extend to other grid-connected renewable power system.

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