Research Article

Reactive power control of grid-connected solar photovoltaic system

Naveen Gira[1], Anil Kumar Dahiya[2]

[1]Department of Electrical Engineering, Research Scholar, National Institute of Technology, Kurukshetra, India
[2]Department of Electrical Engineering, Associate Professor, National Institute of Technology, Kurukshetra, India
[1]giranaveeen@yahoo.com

Article History: Received: 11 January 2021; Revised: 12 February 2021; Accepted: 27 March 2021; Published online: 10 May 2021

Abstract: Solar Photo Voltaic (SPV) based distributed generation is providing a clean and green energy to meet human needs nowadays. In grid-connected mode, most of the capacity of converter circuit is under-utilized as peak power is available for a small duration in the daytime and no utilization during the night. The converter used for PV system may be modified to work as STATCOM, that is capable to convert DC to AC and can compensate reactive power simultaneously. Thus in daytime this modified PV-STATCOM system supply both active and reactive power and in the night it will supply only reactive power resulting in better utilization of Power Conditioning System (PCS). In this paper, modified PV-STATCOM is tested in the grid-connected mode through simulation in MATLAB/Simulink/SimPower under various operating conditions. The proposed system supply active and reactive power locally in the grid-connected load resulting in less burden on the grid.

Key words: STATCOM, Solar Photovoltaic, Active and Reactive power, Simulink

1. Introduction

Solar photovoltaic-based electricity generation has already shown potential at both small and large scales. However, intermittent availability of SPV generation causes the underutilization of the PCS of SPV. In addition, peak power output of SPV is hardly available for most of the time even when Sun shines brightly. For proper utilization of the PCS capacity, combining PV and STATCOM have been suggested in numerous research papers [1,2,11–14,3–10]. These small rating units of PV generation is near to consumers such as roof-mounted mode contribute significantly to the overall generation. In this paper, the notion of PV-STATCOM is studied to supply reactive power and real power at distribution levels along with improved utilization of PCS. The effectiveness of the system is analyzed under variable load conditions with variable irradiation and fixed temperature. Modeling of PV-STATCOM compatible with the grid code requirements is demonstrated in [13], while optimal sizing and siting are explained in [12]. A comprehensive review of the concerns caused by the penetration levels of SPV to the grid discussed in [7]. PV-STATCOM with the ability to extract maximum power integrated into grid displayed in [15]. PV-STATCOM with an objective to avoid instable operation of the induction motor under fault is discussed in [16]. The combination of PV-STATCOM is used to mitigate small voltage variations at distribution level [11], while it is used to improve grid power transmission limits with new control technique [17]. A PV-STATCOM is used for reactive power compensation at night [18]. Reactive power control based on SPV and wind generation is demonstrated by using Fuzzy based controller [14]. Similarly, reactive power control along with reduced harmonics explained in [19]. Short-term voltage variation mitigation with reactive power compensation is done with PV-STATCOM [11]. Implementation of various multilevel converter configuration may be done with PV-STATCOM operation mode for power quality improvement [4,5,20,21].

2. System Models

The single line diagram representation of the proposed PV-STATCOM connected in power distribution network is displayed in Figure 1. SPV setup is coupled at the DC link capacitor of STATCOM through the circuit breaker. The breaker is switched on at 500 milliseconds when PV attains its rated voltage. The boost converter, connected between PV panel and DC capacitor, is utilized to increase voltage level of solar panel. The STATCOM converter is coupled to the Point of Common Coupling (PCC) via LCL filter. A variable load containing active and reactive components is connected at the PCC. The PV-STATCOM is functioning in the grid-connected mode. The PV-STATCOM regulates power flow from AC to DC side in both directions. This function is achieved by dq reference control method. The total complex power exchange by the PV-STATCOM should be within the converter rating, however the main objective is to transfer real power and the reactive power magnitude depend on the spare capacity on converter rating. Thus, the proposed system can supply reactive power up to its current rating in the night and will supply limited reactive power in daytime. The grid supply power to the load at a rated voltage of 400 volts. A system model along with controller has been developed using MATLAB/Simpower to get the results for analysis and conclusion.

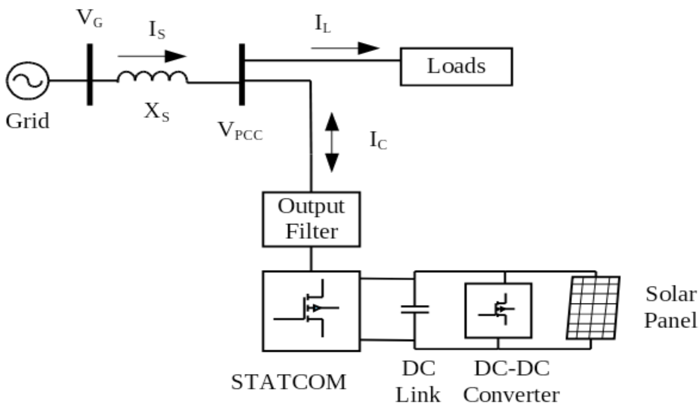

Figure 1. A single line representation of PV-STATCOM in power system.

Where,

V_G = Grid voltage, V_{PCC} = PCC voltage, X_S = Line reactance, I_C = Converter current,
I_S = Grid current, I_L = Load current.

2.1. PV Module

PV cells comprise p-n junction diode, connected in series or parallel to form PV Module. Set of PV module makes PV array. The practical photovoltaic setup includes the connection of resistance in series and parallel, namely Rs and Rsh. The single diode model of PV cell is displayed in Figure 2 and the photovoltaic output current is given by equation (1).

$$I_0 = I_{pv} - I_d \left[\exp\left\{ \frac{q\left(V_0 + I_0 R_s\right)}{N_s A K T_{ak}} \right\} - 1 \right] - \frac{V_0 + I_0 R_s}{R_{sh}} \tag{1}$$

Where,

I_d = Module Diode Saturation Current, I_{pv} = Photovoltaic Current, I_o =Photovoltaic Output Current, V_o = Photovoltaic Output Voltage, I_{rr} = Reverse Saturation Current,

I_{sh} = Shunt Current, I_{scr} = Module Short Circuit Current, T_{ak} = Actual temperature in °K, R_s = Series Resistance, q= The charge of electron ($1.6021*10^{-19}$C), R_{sh} = Shunt Resistance, K= Boltzmann Constant ($1.38065*10^{-23}JK^{-1}$), T_{rk} = Reference temperature in °K, A= The Diode Ideality Constant.

Reverse Saturation Current I_{rr} is,

$$I_{rr} = \frac{I_{scr}}{\left[\exp\left(\frac{qV_{oc}}{KAN_s T_{rk}} \right) - 1 \right]} \tag{2}$$

Diode saturation current I_d is influenced by the temperature of solar panel, given as below.

$$I_d = I_{rr} \left(\frac{T_{ak}}{T_{rk}} \right)^3 \exp\left(\frac{qE_g}{KA} \right) \left(\frac{1}{T_{rk}} - \frac{1}{T_{ak}} \right) \tag{3}$$

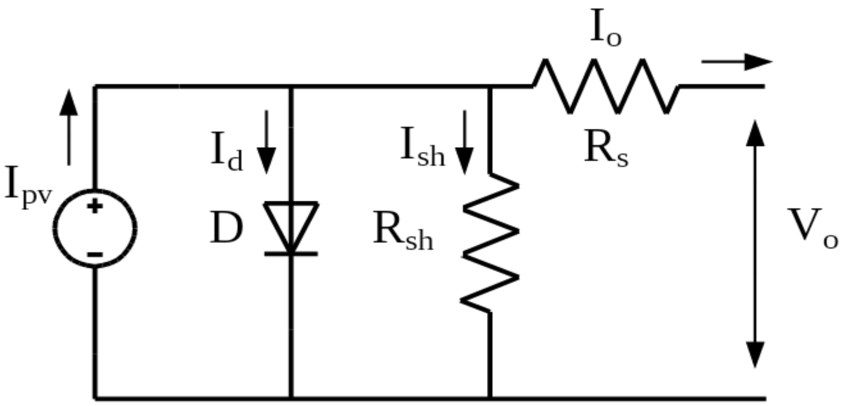

Figure 2. Single diode equivalent circuit of the solar PV cell

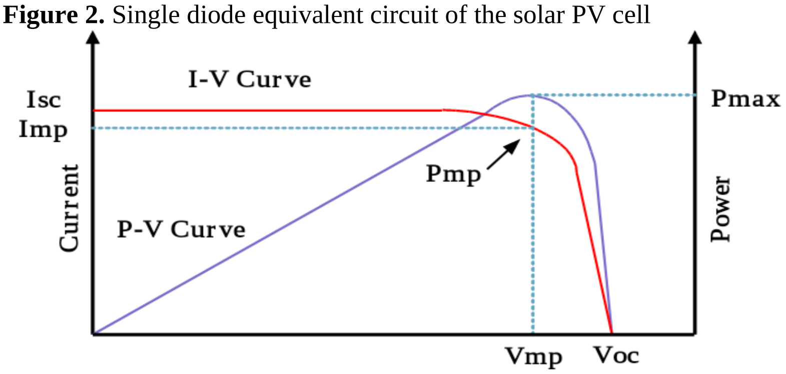

Figure 3. P-V, I–V curve characteristics of a solar PV

The P-V, I-V curve of SPV array are displayed in Figure 3. It shows that variations in V_{PV} of the PV array do not result in large variations in I_{PV}. The PV array can be assumed as constant current source. Though, if the V_{PV} exceeds a threshold point, the current reduces significantly [22].

2.2. DC-DC Boost Converter

A boost converter is connected between PV array and DC link capacitor to increase the voltage of SPV system. The converter duty cycle is calculated taking current and voltage of SPV system. The change in the duty cycle performs the pulse width modulation based switching of the device.

2.3. STATCOM

STATCOM is mainly used in power system to compensate reactive power. The STATCOM improves stability and voltage profile of the system. Classification of STATCOM is based on structural configuration, control method, and signal conditioning. The operating conditions of STATCOM defined in Table 1, assuming the grid voltage as a reference (δ=0). The reactive power compensation is done by controlling the current in an inductor connected between grid and STATCOM converter. The direction and magnitude of the inductor current are controlled by the voltage difference across the inductor. The grid voltage is almost constant hence, STATCOM inverter voltage is controlled by controlling the charging and discharging level (voltage) of capacitor voltage.

Table 1. Operating Conditions of STATCOM [8]

Power Transfer			Voltage Relation
STATCOM	⟷	Utility Grid	
P	⟶	P	$\delta < 0$
	⟵		$\delta > 0$
Q	⟶	Q	$\lvert V_i \rvert > \lvert V_{PCC} \rvert$
	⟵		$\lvert V_i \rvert < \lvert V_{PCC} \rvert$

Where,

P = Active power, V_i = STATCOM voltage, Q = Reactive power, V_{PCC} = Voltage at PCC, δ= Voltage angle

The DC link voltage is regulated using active power flow between grid and capacitor by controlling the voltage angle (δ) of the inverter. If voltage angle of STATCOM bus is lesser as compared to grid voltage angle, real power flow towards STATCOM that charge the capacitor and vice versa. V-I characteristic of STATCOM is displayed in Figure 4. It shows the exchange of reactive power among STATCOM and utility grid [3,8]. V_{Ref} is the nominal voltage at PCC.

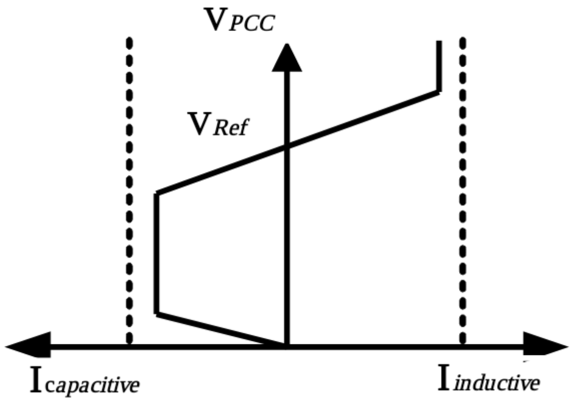

Figure 4. V-I Operating characteristic of STATCOM.

2.4. STATCOM Controller

The function of STATCOM is to control the power flow from AC to DC bus in both directions. The regulation of power is executed using a controller widely known as dq0 reference controller as shown in Figure 5. The controller uses STATCOM current, grid current, grid voltage and DC voltage as the inputs. The Phase Locked Loop (PLL) is used to calculate the angle to extract the dq0 values given in the equation (4) and then grid voltages are used to generate the pulses of the converter. The direct axis current is in phase and the q axis component is in quadrature to the voltage, hence q component used for voltage regulation and reactive power compensation and d axis component utilized for DC voltage control that done by active power control [23].

$$\begin{bmatrix} i_{load\_d} \\ i_{load\_q} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & cos\left(\theta - \frac{2}{3}\pi\right) & cos\left(\theta - \frac{4}{3}\pi\right) \\ -sin\theta & -sin\left(\theta - \frac{2}{3}\pi\right) & -sin\left(\theta - \frac{4}{3}\pi\right) \end{bmatrix} \begin{bmatrix} i_{load\_a} \\ i_{load\_b} \\ i_{load\_c} \end{bmatrix} \quad (4)$$

Accordingly, the PWM reference voltages (V_{ref_a}, V_{ref_b}, V_{ref_c}) of PV-STATCOM setup are attained by the reverse d-q transformation as specified in (5).

$$\begin{bmatrix} v_{ref\_a} \\ v_{ref\_b} \\ v_{ref\_c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos\left(\theta - \frac{2}{3}\pi\right) & -\sin\left(\theta - \frac{2}{3}\pi\right) \\ \cos\left(\theta - \frac{4}{3}\pi\right) & -\sin\left(\theta - \frac{4}{3}\pi\right) \end{bmatrix} \begin{bmatrix} V_{d\_ref} \\ V_{q\_ref} \end{bmatrix} \quad (5)$$

It is worth notable that both active and reactive power may be generated simultaneously. The block diagram of STATCOM controller is shown in Figure 5. The DC voltage regulator maintains the DC link voltage to a constant value that is also a function of the DC link capacitor rating. Although, the controller parameters are not optimal values. The optimization of the controller parameters done using Ziegler Nichols method. Nevertheless, the chief objective of this work is to propose a concept of improved utilization of PV-STATCOM at the distribution level. DC voltage regulator is a simple controller with proportional and integral gain, added to the main signal from dq transformation of load currents. Grid voltage utilized to extract the sinθ and cosθ later used to transform the dq components to voltage signals. These d-q components multiplied with linking reactance to get the equivalent voltage, fed to the d-q to ab transformation after addition to the controller output. The output of the controller is given to the subsystem containing the logic to generate the firing pulses at the frequency of 25 kHz.

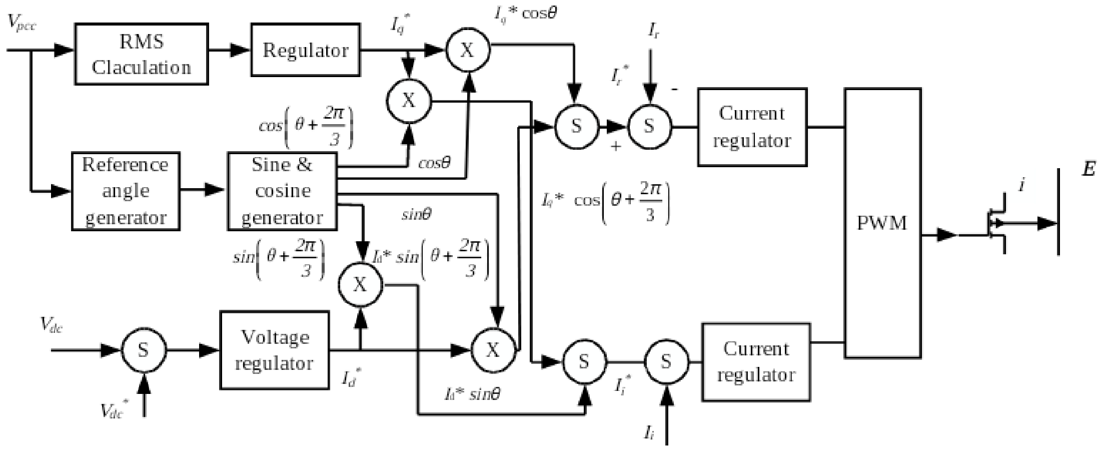

Figure 5. Block diagram of STATCOM Controller [1]

3. Simulation Results

Detailed simulation for different conditions has been executed in the MATLAB/Simulink software. The ratings of various system components are given in Table 2. Ads displayed in the results, Solar PV is connected to the grid through STATCOM at DC link at 500 milliseconds in the simulation. Both active and reactive load varied from 3.5+j0.500 kVA to 4.5+j0.900 kVA for a duration of 1450 milliseconds at the instant 750 milliseconds. The solar irradiation level is reduced to zero at instant 2800 milliseconds to study the working of PV-STATCOM for reactive power control during the night, as shown in the Figure 6.

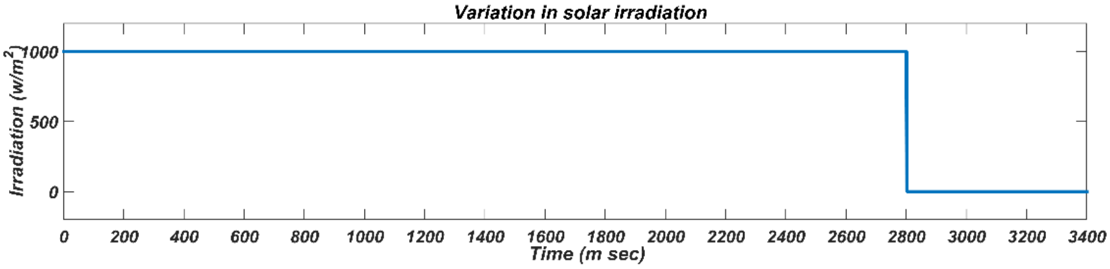

Figure 6. Variation in solar irradiation level

Table 2. Ratings of Various Components in the Detailed Model.

120 kV, 50Hz	Voltage	Grid
50 MVA	SCC	
0.0127 Ω/kM	Resistance	Line

0.933 H/kM	Inductance	
20 kM	Length of Line No. 1	
10 kM	Length of Line No. 2	
0.007142×2 H, 0.7e^{-6} F	LCL Filter	STATCOM
400 V RMS / 700V	Voltage Rating (AC/DC)	
0.9 mF	Capacitor	
4.5 kW, 0.9 kVAR	Maximum Power	Load
640 W	$P_{Max,0}$	PV Array
21.1 V	$V_{OC,0}$	
3.8 A	$I_{SC,0}$	
2×287	No. of cells in Module	

The active and reactive power output of PV-STATCOM is shown in Figure 7. The modified solar system supply a constant active power of 640 watts and variable reactive power within the inverter current rating limit. The performance of PV-STATCOM is simulated by reducing irradiation to zero at 2800 milliseconds. Thus, during the night, the proposed system control reactive power only while active power delivered to the grid is reduced to zero. It is clear from Figure 8, that burden on the grid reduces when PV-STATCOM is connected to the grid.

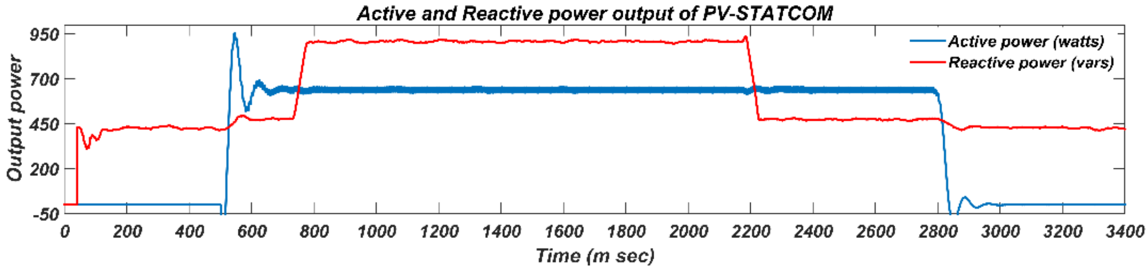

Figure 7. Active power supplied by the PV-STATCOM to the load.

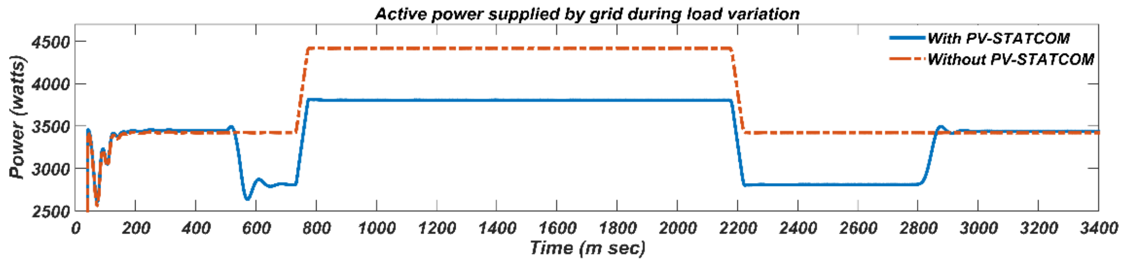

Figure 8. Active power supplied by the grid to the load.

The modified solar system meets the reactive power requirement of the load, resulting in the reactive power drawn from the grid become almost zero as shown in Figure 9. Reactive power compensation near the consumer connection is much more effective as it reduces the VA burden on grid and generators resulting in better power system operation. The DC link voltage remains constant during the simulation period except for slight variation in magnitude at the instant of switching moments as shown in Figure 10.

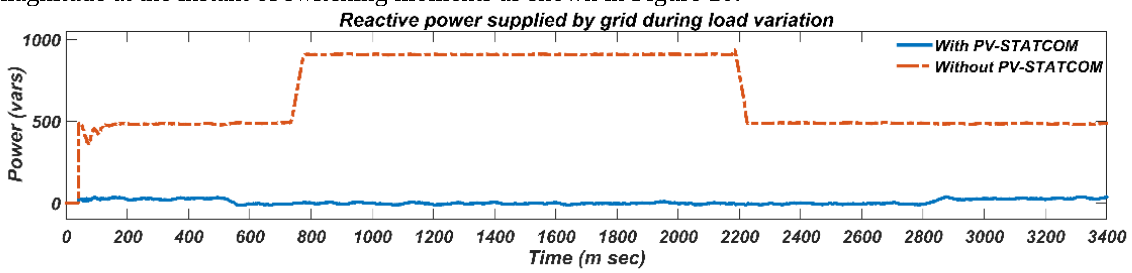

Figure 9. Reactive power provided by the grid to the load.

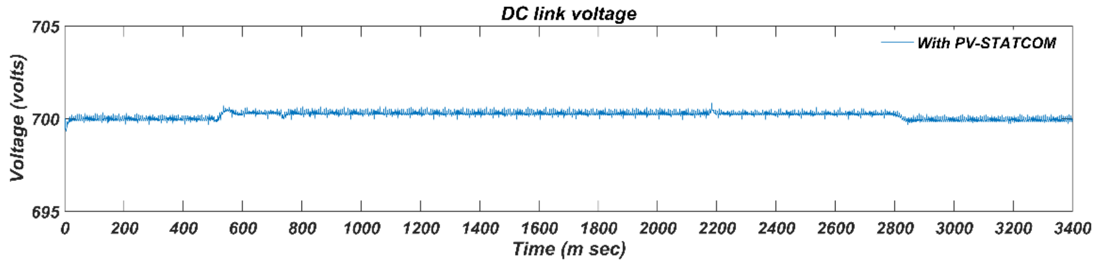

Figure 10. Variations in the DC link voltage

The PCC per unit voltage with and without PV-STATCOM is shown in Figure 11. The marginal improvements in the voltage profiles have been observed from the Figure 11. The voltage regulation of power system also improves due to the reactive power compensation at the load point. The variation in the PV output current is shown in the Figure 12,

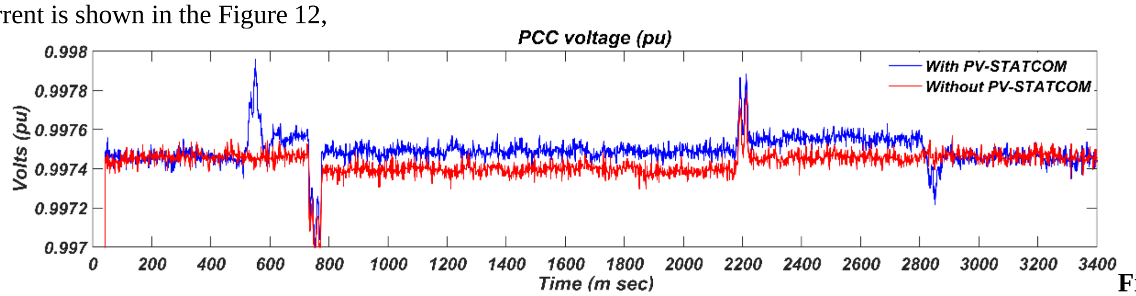

Figure 11. Per unit voltage at PCC

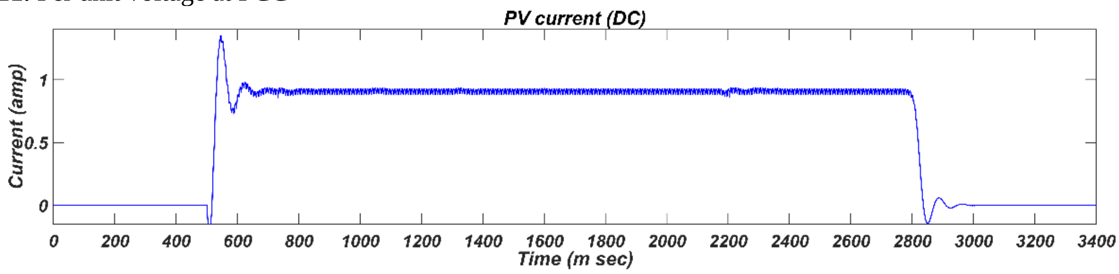

Figure 12. Variation in the PV output current

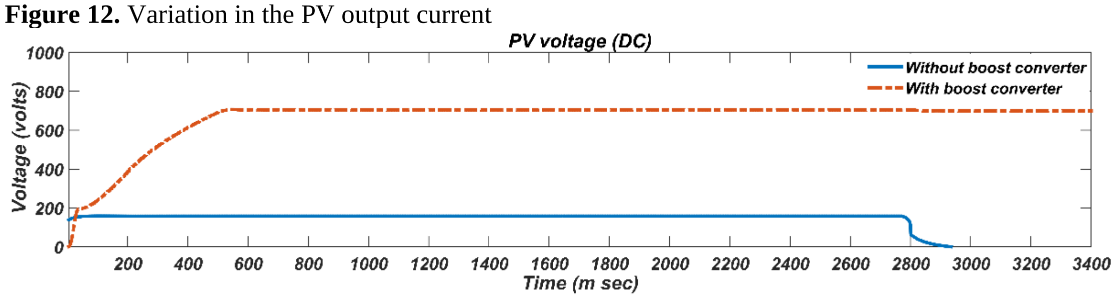

Figure 13. Solar PV output voltage.

Solar PV output voltage after the DC-DC boost converter displayed in Figure 13. The voltage remains constant in the varying load conditions. It is evident from the Figures (7-9), PI-based controller enables the PV-STATCOM to compensate the load requirements of the grid. At 500 milliseconds, PV connected to STATCOM through the circuit breaker. During the simulation, the active power requirement varies from 3.5 kW to 4.5 and reactive power demand varies from 500 VAR to 900 VAR. The proposed system supply reactive power according to the load requirement and constant real power of 640 watts. However, a constant DC link voltage of 700 volts maintained throughout the simulation with the minor fluctuations and current fall to zero when irradiation is reduced to zero value. The solar PV is supplying a DC current of 0.9 Amps operating at around 700 volts under standard operating conditions. Almost 400 volts is maintained at the PCC during the load variation.\

4. Conclusion

Integration of Solar PV to STATCOM to feed active and reactive power at PCC for reducing the burden on the grid is studied in this research. A detailed model of STATCOM and solar PV is developed in MATLAB/Simulink and a simulation study is carried out for variable irradiation and fixed temperature. It is observed from the simulation results that the solar PV based STATCOM is capable of supplying constant active power at PCC during the daytime. In addition to this, solar PV based STATCOM is effective for compensation of reactive power under variable load conditions during day and night. It is also evident from the simulation results that the voltage at PCC is improved marginally using solar PV-STATCOM. In this paper, the results are achieved using a PI-based controller, which is simple and easy to implement. The performance of the proposed system may improve by replacing the PI controller with ANN, Fuzzy and GA based controller. The selective parameter control may also be explored for economic consideration.

References

1. Chen Chao-Shun, Lin Chia-Hung, Hsieh Wei-Lin, Hsu Cheng-Ting, Ku Te-Tien. Enhancement of PV Penetration With DSTATCOM in Taipower Distribution System. IEEE Transactions on Power Systems. 2013;28(2):1560–7. Doi: 10.1109/TPWRS.2012.2226063.
2. Chidurala Annapoorna, Saha Tapan Kumar, Mithulananthan N. Power quality enhancement in unbalanced distribution network using Solar-DSTATCOM. 2013 Australas. Univ. Power Eng. Conf. AUPEC 2013. 2013. p. 1–6.
3. Das J C. Application of STATCOM to an Industrial Distribution System Connected to a Weak Utility System. IEEE TRANSACTIONS ON INDUSTRIAL APPLICATIONS. 2016;52(6):5345–54.
4. Hussain Ikhlaq, Kandpal Maulik, Singh Bhim. Grid integration of single stage SPV-STATCOM using cascaded 7-level VSC. International Journal of Electrical Power & Energy Systems. 2017;93:238–52. Doi: 10.1016/j.ijepes.2017.06.005.
5. Junbiao Han, Khushalani- Solanki Sarika, Solanki Jignesh, Schoene Jens. Study of unified control of STATCOM to resolve the Power quality issues of a grid-connected three phase PV system. 2012 IEEE PES Innov. Smart Grid Technol. IEEE. 2012. p. 1–7.
6. Kandpal Maulik, Hussain Ikhlaq, Singh Bhim, Chandra Ambrish, Al-Haddad Kamal. Control of grid tied SPV-DSTATCOM system using adaptive RLS technique. 2016 IEEE Int. Conf. Power Electron. Drives Energy Syst. IEEE. 2016. p. 1–6.
7. Karimi M., Mokhlis H., Naidu K., Uddin S., Bakar A.H.A. Photovoltaic penetration issues and impacts in distribution network – A review. Renewable and Sustainable Energy Reviews. 2016;53:594–605. Doi: 10.1016/j.rser.2015.08.042.
8. Latran Mohammed Barghi, Teke Ahmet, Yoldas Yeliz. Mitigation of power quality problems using distribution static synchronous compensator : a comprehensive review. IET Generation, Transmission & Distribution. 2015;8(7):1312–28. Doi: 10.1049/iet-pel.2014.0531.
9. Lin C. H., Chen C. S., Hsieh W. L., Hsu C. T., Chuang H. J., et al. Optimization of photovoltaic penetration with DSTATCOM in distribution systems. 2012 IEEE Int. Conf. Power Syst. Technol. IEEE. 2012. p. 1–6.
10. Liu Xiao, Cramer Aaron M., Liao Yuan. Reactive-power control of photovoltaic inverters for mitigation of short-term distribution-system voltage variability. 2014 IEEE PES T&D Conf. Expo. IEEE. 2014. p. 1–5.
11. Liu Xiao, Cramer Aaron M., Liao Yuan. Reactive power control methods for photovoltaic inverters to mitigate short-term voltage magnitude fluctuations. Electric Power Systems Research. 2015;127:213–20. Doi: 10.1016/j.epsr.2015.06.003.
12. Luo Lizi, Gu Wei, Zhang Xiao-Ping, Cao Ge, Wang Weijun, et al. Optimal siting and sizing of distributed generation in distribution systems with PV solar farm utilized as STATCOM (PV-STATCOM). Applied Energy. 2018;210(August 2017):1092–100. Doi: 10.1016/j.apenergy.2017.08.165.
13. Nanou Sotirios I., Papathanassiou Stavros A. Modeling of a PV system with grid code compatibility. Electric Power Systems Research. 2014;116:301–10. Doi: 10.1016/j.epsr.2014.06.021.
14. Rezaei F., Esmaeili S. Decentralized reactive power control of distributed PV and wind power generation units using an optimized fuzzy-based method. International Journal of Electrical Power & Energy Systems. 2017;87:27–42. Doi: 10.1016/j.ijepes.2016.10.015.
15. Toodeji H., Farokhnia N., Riahy G.H. Integration of PV module and STATCOM to extract maximum power from PV. Electr. Power Energy Convers. Syst. 2009. EPECS ’09. Int. Conf. 2009.

16. Varma Rajiv K, Rahman Shah Arifur, Sharma Vinay, Vanderheide Tim. Novel control of a PV solar system as STATCOM (PV-STATCOM) for preventing instability of induction motor load. 2012 25th IEEE Can. Conf. Electr. Comput. Eng. IEEE. 2012. p. 1–5.
17. Varma Rajiv K., Rahman Shah Arifur, Vanderheide Tim. New Control of PV Solar Farm as STATCOM (PV-STATCOM) for Increasing Grid Power Transmission Limits During Night and Day. IEEE Transactions on Power Delivery. 2015;30(2):755–63. Doi: 10.1109/TPWRD.2014.2375216.
18. Varma Rajiv K., Rahman Shah Arifur, Mahendra A. C., Seethapathy Ravi, Vanderheide Tim. Novel nighttime application of PV solar farms as STATCOM (PV-STATCOM). 2012 IEEE Power Energy Soc. Gen. Meet. IEEE. 2012. p. 1–8.
19. Seo Hyo-ryong, Kim Gyeong-Hun, Jang Seong-jae, Kim Sang-yong, Park Sangsoo, et al. Harmonics and reactive power compensation method by grid-connected Photovoltaic generation system. 2009 Int. Conf. Electr. Mach. Syst. 2009. p. 1–5.
20. Sridhar V., Umashankar S. A comprehensive review on CHB MLI based PV inverter and feasibility study of CHB MLI based PV-STATCOM. Renewable and Sustainable Energy Reviews. 2017;78(May 2016):138–56. Doi: 10.1016/j.rser.2017.04.111.
21. Thathan Manigandan, Alexander Albert. Modelling and analysis of modular multilevel converter for solar photovoltaic applications to improve power quality. IET Renewable Power Generation. 2015;9(1):78–88. Doi: 10.1049/iet-rpg.2013.0365.
22. Singh Moirangthem Dennis. Application of Artificial Neural Networks in Optimizing MPPT Control for Standalone Solar PV System 2014:162–6.
23. Toodeji H., Fathi S.H., Farokhnia N. Using current-based MPPT method in new integrated system of PV module and STATCOM. 2010 5th IEEE Conf. Ind. Electron. Appl. IEEE. 2010. p. 1028–33.