PV Module integration with STATCOM for Reactive Power Compensation

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Abstract—**Generation and Transmission of power is a complex process, which requires the working of many components of the power system so as to deliver the maximum power output. We need to manage the flow of Active and Reactive power in an efficient and economic way so as to improvise the performance of power systems. Thus, a Static synchronous compensator (STATCOM) integrated with Photovoltaic (PV) module can be used to optimize the reactive power flow by varying the level of voltage for the Voltage Source Converter with respect to source bus voltage. By connecting PV modules directly to STATCOM, the requirement of DC-DC Converter can be completely overcome as STATCOM regulates DC voltage at optimal value. In the present integrated study system using PV and STATCOM simulated in Simulink software, the effect of varying solar irradiance and changing the number of solar cell modules on the reactive power have been studied.**

Keywords-Voltage Source Converter; solar irradiance; reactive power; PV module.

I. INTRODUCTION

Among the renewable energy resources, the photovoltaic (PV) effect is considered to be the most essential and primary sustainable resource as it is available in abundance [1].Although this energy is intermittent in nature, PV modules can be well integrated with Maximum Power Point Trackers (MPPT) to generate maximum power even in the conditions of minimum irradiance and maximum temperature.

This ability of PV cells to harness Direct current from sunlight can be utilized to compensate for the real and reactive power flowing over the transmission network. Unnecessary voltage drops lead to increased losses which need to be supplied by the voltage source which results in outages in the line due to increased stress on the system to carry the imaginary power. Compensation of reactive power helps in better transient response to faults and disturbances. It is very much required so that the lines can be relieved of carrying the reactive power, which is better actually provided close to the generators or the loads.

A STATCOM is a compensating device used in regulating the flow of reactive power in the network and is independent of other system parameters. It consists of a three phase inverter (generally a PWM inverter) with Metal Oxide Field Semiconductor Field Effect Transistor (MOSFETs) or Insulated Gate Bipolar Transistors (IGBTs), a Direct Current (DC) capacitor which provides the D.C voltage for the inverter, a reactor which links the inverter output to the Alternating Current (AC) on supply end, filter components used in filtering out high frequency components generated due to the PWM inverter. On the DC side capacitor, a three phase sinusoidal voltage is generated by inverter which is synchronized with the AC supply. The inductor links the above voltage to supply end [2]. STATCOM is an efficient and highly used compensator which has been introduced in detail in many literatures [3]-[5].

Arun Bhaskar et al. discussed the usage of utilizing Photovoltaic (PV) SolarFarm (SF) under idle conditions as Static Synchronous Compensator (STATCOM), to regulate the point of common coupling voltage when the wind farm supply the power to the grid.[6]

Rajiv K. Varma et al. designed a novel control concept by which a photovoltaic solar farm is made to operate as a STATCOM – a Flexible AC Transmission System (FACTS) device and used to increase transient stability and consequently the power transfer limit of the transmission network.[7] Toodeji et al. discussed that by connecting PV module directly to the STATCOM, a PV module can always work in its optimal operating point even if DC-DC converter is not connected as STATCOM helps to regulate DC voltage at the optimal value.[8]

In the present study PV Modules are integrated with a grid connected STATCOM .In the first part PV Modules have been studied in depth. Different numbers of PV Modules have been connected and their presence on the reactive power compensation has been discussed.

In the second part the effect of varying solar irradiation on the generation or absorption of reactive power through the compensator has been tabulated.

II. DETAILED SYSTEM

Fig.1 shows a three phase transmission system consisting of three voltage sources with varying loads (loads not shown in figure) and PV modules integrated with a STATCOM.

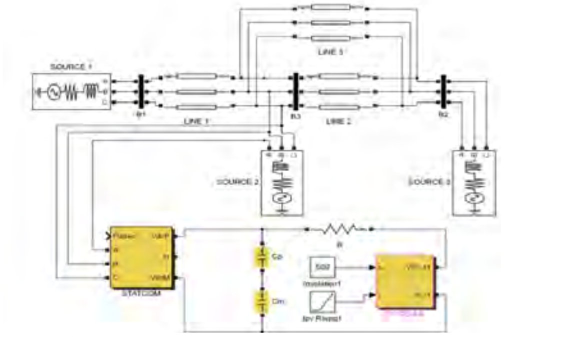

Figure 1. Proposed Integrated System using STATCOM and PV

A. STATCOM

A STATCOM rated as 100-Mvar is used to regulate voltage on a three-bus 500-kV system. The 48-pulse STATCOM uses a VSC built of four 12-pulse three-level GTO inverters. The four sets of three-phase alternating voltages obtained at output of the four three-level inverters are applied to the secondary windings of four phase-shifting transformers (-15 deg., -7.5 deg., 7.5 deg., +7.5 deg. phase shifts). The fundamental components of voltages obtained on the 500 kV sides of the transformers are added in phase by the serial connection of primary windings. Under steady-state operation the control system of STATCOM keeps the fundamental component of the VSC voltage in phase with the system voltage. When the voltage generated with VSC is higher (or lower) than the system voltage, the STATCOM generates (or absorbs) reactive power. The level of reactive power depends on the VSC voltage magnitude and on the transformer leakage reactance. The fundamental component of VSC voltage is controlled by varying the DC bus voltage. In order to vary the DC voltage, and so the reactive power, the VSC voltage angle (alpha) which is normally kept close to zero is phase shifted temporarily. This VSC voltage lag or lead results in a temporary flow of active power which results in an increase or decrease of capacitor voltages. Fig 2 shows the basic circuit of a STATCOM. The active and reactive power exchanged between the networks is given by:

$$Q = \frac{V\,(U - Ec\,Cos(\delta))}{X} \quad (1)$$

If the amplitude of the output voltage phasor (*Ec*) is increased above the amplitude U of the AC voltage (*U*), then the current phasor leads the voltage phasor and current flows from the converter to the AC system and the converter generates reactive (capacitive) power to the system. If the amplitude of the output voltage phasor is decreased below that of the AC system voltage phasor, then the reactive current flows from the AC system to the converter, and the converter absorbs reactive (inductive) power from the AC system.

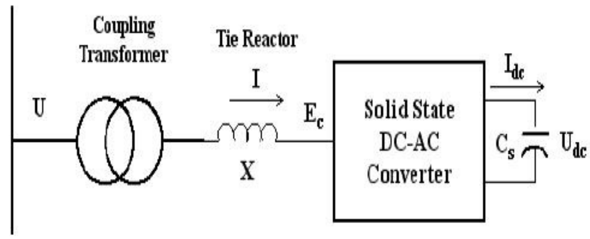

Figure 2. Basic Circuit of a STATCOM

B. PV Module

A PV module can accommodate a number of interconnected solar cells captured in a single unit [9].

In order to calculate the power extracted from the PV modules and the module current-voltage (I-V) characteristics, it is important to model a solar cell. The solar cell model takes into account the variation of the photovoltaic current with variation in temperature and irradiance [10]. The current 'I' produced by the photovoltaic module is obtained as

$$I = I_L - I_D \quad (2)$$

The diode current is given by the Shockley equation:

$$I_D = I_0\left[\exp\left(\frac{q(V+IRs)}{\gamma kTc}\right) - 1\right] \quad (3)$$

Where

I_D is the diode current

I_L denotes the photoelectric current under a given condition of radiation and of temperature

V is the output voltage [V]

I_0 is the saturation diode current [A]

γ denotes the form factor that represents an index of the cell failing

Rs is the series resistance of the cell [Ω]

q is the electric charge ($1.602*10^{-19}$C)

k is the Boltzmann's constant ($1.381*10^{-23}$K)

Tc is the module temperature [K].

By substituting (2) in (1), we obtain the following generic equation

$$I = I_L - I_0\left[\exp\left(\frac{q(V+IRs)}{\gamma kTc}\right) - 1\right] \quad (4)$$

Fig 3. shows the modelling of a PV module using above equations in Simulink.

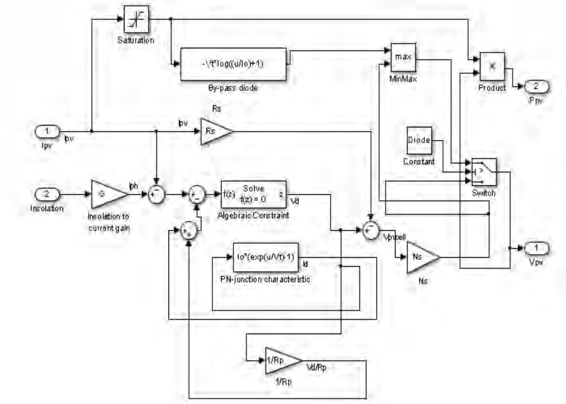

Figure 3. PV Module using SIMULINK

III. STATCOM CONTROLLER

A STATCOM Controller comprises of a abc to dqo converter, a Phase Locked Loop (PLL), a Proportional Integral (PI) controller, a Voltage Regulator, a Current regulator along with a firing pulse generator. If error signal is obtained when comparing the reactive power(reference) Q_{ref} with the reactive power Q_m (measured) at the load points. The PI Controller starts processing the error signal and then generates the required angle to drive the error to zero. The PLL which generates a ramp signal which fluctuates between 0° and 360°, synchronized in phase with the input voltage Va [11]. PWM controls have become a practical option for transmission system applications using VSC-based controllers. This is happening because of some recent developments in power electronic switches in which the high switching losses are absent which is not the case in GTOs [12].

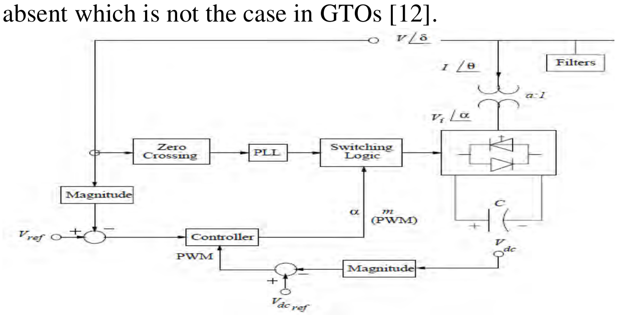

Figure 4. STATCOM with PWM voltage control

IV. SIMULATION RESULTS

The proposed system consisting of a STATCOM integrated with PV modules has been studied under three parts. In the first part the PV module is totally removed and the system is viewed having only STATCOM to provide reactive power compensation. In the second part the number of Solar cell modules is varied and its impact on the generation and absorption of reactive power is been tabulated. In the last part variation of irradiance has been realized throughout the day and its effect has been mentioned.

TABLE 1. DETAILS OF SAMPLE SYSTEM

Parameters	Ratings of the sample system	
Voltage Source 1	Voltage Rating	400kV, 50Hz
	SC Level	8500 MVA
Voltage Source 2	Voltage Rating	400kV , 50Hz
	SC Level	9000 MVA
Voltage Source 3	Voltage Rating	400kV, 50Hz
	SC Level	6500 MVA
Line Parameter	Resistance	R1=0.02546Ω/km R0=0.3864 Ω/km
	Inductance	L1=0.93373x10^{-3} H/km Lo=4.1264x10^{-3} H/km
	Capacitance	C1=12.74x10^{-9}F/km C0=7.75x10^{-9} F/km
	Line 1 length	100 km
	Line 2 length	50km
	Line 3 length	150km
STATCOM	12 pulse 3 level GTO Inverter	100 MVAR
Transformers	Four Phase Shifting Transformers	-15°,-7.5°,7.5°,+7.5°
PV Array	Pmax	100 W
	Voc	22.2 V
	Isc	5.4 5 A
No. of Series Modules used		5,10,20,30,40

A. *Study system with STATCOM without PV Module connected*

STATCOM provides leading or lagging VARS required by the loads in the proposed transmission network. The results show that STATCOM is producing reactive (positive VARs) as the loads connected are highly inductive as given in Table 2 and Fig.5.

TABLE 2. STATCOM WITHOUT PV MODULES

Primary Voltage(pu)	Secondary Voltage(pu)	Secondary Current(pu)	Vdc(Volts)	Q(MVAR)
-0.08496	1.962x10^{-5}	1.021	1.701 X10^{4}	79.13

B. *Effect of Varying Number of Solar modules in Series*

In the present system the solar modules connected to the STATCOM have been varied. It is observed in Table 3 that by increasing the number of PV modules in series, the VAR requirement by the sources and loads decreases and also the dc voltage required by the voltage source converter for STATCOM operation decreases considerably. In Table 3 it is also shown that VARS up to (22.05MVAR) are produced by connecting 40 PV modules with STATCOM for simulation time of t=1.0sec. Fig. 6 shows that by integrating PV Modules with STATCOM the reactive power requirement for the connected loads and supply sources is fully met. The reactive power requirement is almost zero at 0.3 sec.

TABLE 3 EFFECT OF VARYING NUMBER OF SOLAR MODULES

No. of Modules in Series	Variation in Q(MVAR)	Variation in Vdc(Volts)
5	23.32	$1.668x10^4$
10	22.50	$1.663x10^4$
20	22.25	$1.662x10^4$
30	22.10	$1.661x10^4$
40	22.05	$1.660x10^4$

C. *Effect of Varying Solar Irradiance*

Solar modules are subjected to varying levels of irradiance throughout the day. Some of the insolation levels at which considerable changes in the production of VARS was noticed have been tabulated in Table 4.By increasing the irradiance of the solar cells the VARS required decreases gradually and when it reaches 1000W/m^2, minimum VARS upto (22.05 MVAR) for 40 solar cell modules are consumed for simulation time of time t=1.0 sec.

TABLE 4. EFFECT OF VARYING SOLAR IRRADIANCE

NO. OF SOLAR CELL MODULES IN SERIES=40

Irradiance (W/m2)	Variation in Q(MVAR)	Variation in Vdc(Volts)
100	23.88	$1.668x10^4$
200	23.86	$1.667x10^4$
500	23.38	$1.667x10^4$
1000	22.05	$1.660x10^4$

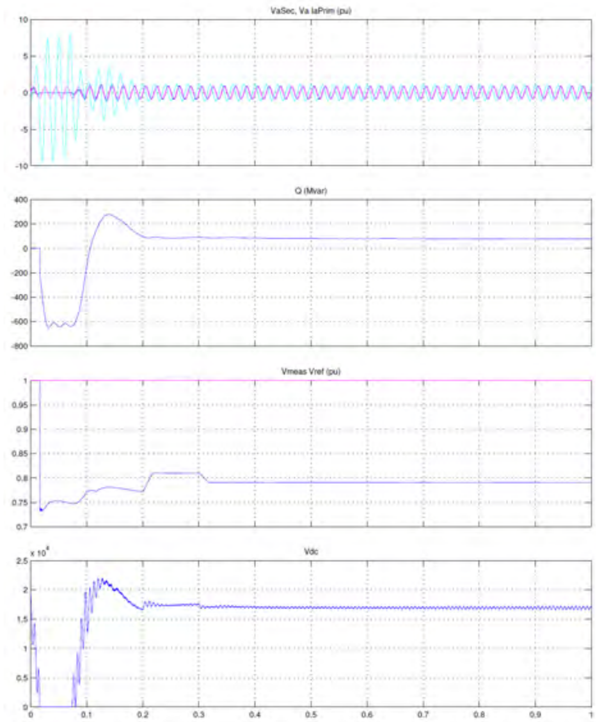

Figure.5 STATCOM without PV Modules

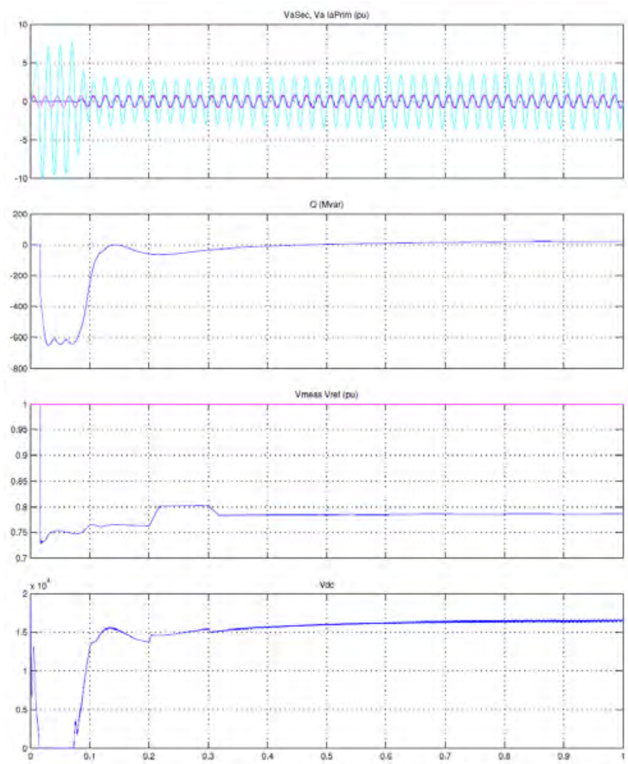

Figure. 6 STATCOM with 40 PV Modules in Series at STC

V. CONCLUSION

In this paper, a STATCOM is used with five different sets of PV modules.

- It is observed that using a PV module with STATCOM helps in relieving the load and the main supply sources of the reactive power demand as compared to a standalone STATCOM connected to the grid.
- Elimination of a DC-DC Converter which is required with a Solar panel leads to reduction in cost and size of the system.
- The PV Modules are tested under different conditions of irradiance and its effect on reactive power generation has been formulated. It is seen that with the increase in irradiance the reactive power requirement decreases and is least under (STC) Standard test conditions (1000W/m^2 and 25°C).

  The required simulations were executed in SIMULINK software and the desired results were obtained.

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