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Performance Analysis of Grid connected Solar Farm by Power Factor Control

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ABSTRACT

Performance of any electrical system mostly depends on the power factor. As power factor governs the flow of active and reactive power, so it is important to control the power factor of the system. If the system has lagging power factor, then it can be compensated by injection of leading component and vice versa for keeping power factor near to unity. In recent past years solar energy has emerged as an important source of energy for utilities. Solar farm is used for conversion of solar energy into electrical energy. Solar farm may be PV-based, CSP or CPV based. It can be used either in standby mode or in conjunction with main grid system to supply the load directly in former case and to support the grid system in different operating condition in later case. In this work Grid connected with solar farm based on PV has been considered. In this work it has been discussed that the connected solar farm can be utilized to improve the power factor of the system by the injection of voltage. Depending upon the power factor of the system the magnitude of the injected voltage varies. The injected voltage is in quadrature with the voltage of grid system. In later part it has also been discussed that the solar farm can also be utilized to support the grid system during fault. For the analysis of performance under fault condition different fault conditions have been considered and simulation/ MATLAB has been used.

Keywords: Power factor; Apparent power;active power; reactive power; Solar Farm;Converters; MPPT; Duty Cycle; MLI; Fuzzy logic controller

1. INTRODUCTION

Most countries in the world uses conventional energy sources to supply electrical power to consumers. The load demand increases every day and it has become a challenging task for utility as well as for engineers to meet this increasing demand scenario with desired power quality. As conventional energy sources face the constraints of their long term availability and distance from the load center so it is desired to find a source of energy which could be used to supply the increased demand of power in conjunction with the main grid and which is near to load center in comparison to conventional energy sources. Solar energy has been emerged as a major source power. Solar farms are used to extract and convert the solar energy. Among different types of solar farms, PV-based solar farms are gaining popularity as these are environment friendly and advancements in power electronics technology has made it possible to extract the solar power more efficiently [1][2]. These solar farms are installed at various places depending upon the installation area availability and load demand to support the main grid supply system through PCC (point of common coupling). At PCC the voltage or current can be injected. Overall efficiency of utility network can be increased by adjustment of power factor which enhance the flexibility of the utility network to supply loads with desired power quality [3]. The voltage or current of the solar farm can be used to adjustment power factor by controlling the phase angle of the injected voltage or current.

This paper proposes a control scheme that improves the performance of grid connected solar farm utility network by injection of voltage in accordance with the power factor of the network. The power

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factor of the network is monitored continuously for a defined range of power factor angle. If the measured value of power factor angle is less than the given range, then this represents a lagging power factor system and a lagging voltage is injected by the solar farm which decreases the angle between voltage and current of the system and thus power factor improves and reaches under the desired limit. In contrast if the measured value of power factor is greater than the given range, then the leading voltage is injected by the solar farm which decreases the angle between the voltage and current and the power factor is again brought back in the desired range and thus power factor is controlled. The magnitude of injected voltage in both cases depends on the magnitude of difference between power factor angle of system and reference power factor angle.

2. EFFECT OF POWER FACTOR ON POWER SYSTEM PERFORMANCE

Power factor plays a vital in the power system. It may be defined as the cosine of the angle between voltage and current of the system. Figure 1 represents a power triangle. If '⊖' is the power factor angle, then:

$$KW = KVA * \cos \tag{1}$$

$$KVAr = KVA * \sin \tag{2}$$

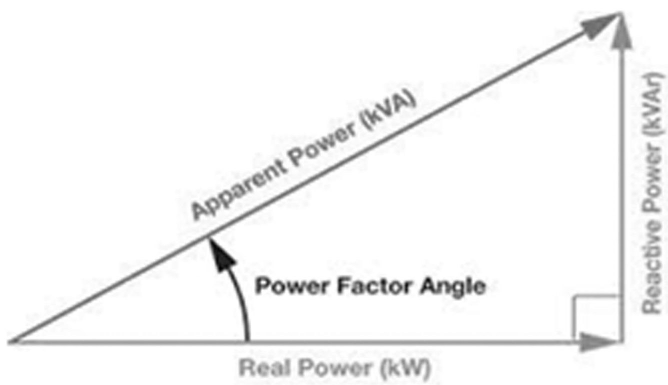

Figure 1: Power Triangle

Equations (1) & (2) are the mathematical expressions of real and reactive power which indicates that power factor directly affects the flow of real and reactive power in the system. Real power is the power dissipated by a load whereas reactive power is absorbed and returned in load due to its reactive. This reactive power oscillates between the source and the reactor or capacitor. The frequency of oscillation is equal to twice the rated value [4]. Commercially reactive power is an unwanted component of apparent power as it increases the KVA rating of source for a particular KW rating. A low power factor indicates presence of large amount of reactive power in the system. This has remarkable negative effect on the normal operation on power system equipment and devices which includes generators, transformers, switchgear and bus-bar, prime-movers and transmission and distribution lines and feeders [5] [6] [7] [8]. The imbalance in generation and absorption of reactive power in the system causes voltage variation in the system. The voltage level goes up when generated reactive power is greater than the absorbed reactive power and vice versa and for flat voltage profile these two must be equal. So to maintain a flat voltage profile this reactive power is required to be controlled in the system [9]. Low lagging power factor results in the system due to the presence of inductive loads which absorb reactive power. Due to this low lagging power factor large size of power conductors are required to transfer power in comparison to high power factor. Though reactive power may be thought as an unwanted component of apparent power in the power system but reactive power is required in power system network for the control of voltage, transmission of active power, and for normal and secure operation of a power system. Hence a proper control of power factor is required for the optimal operation of various components of power system network [10]. To enhance the power transfer efficiency and the system performance, power factor control must be nearer to load end. In power factor control reactive power required by the load is generated and supplied to the load. Thus power factor correction improves the overall performance of the power system which in turn leads to increase in switchgear, starter, and motor life [11].

3. PV-BASED SOLAR FARM

PV-based solar farm uses PV-panels to generate clean and green electricity locally at large scale which is then feed into the grid. The area occupied by solar farm may be anything between 1 acre and 100 acres. Figure 2 represents a simple block diagram of solar farm which shows main components of solar farm. Other components of solar farm are cabling network, step-up transformer and power lines to evacuate power. Solar panel is a collection of solar cells connected together for desired power generation. Cabling network is used to link solar panels. It consists of thin cables from each panel which are then connected to form bigger size cables. These are connected to charge controller and battery system to collect the entire DC power from the panels. As output of solar panel is DC so it is required to convert it into AC before feeding into the grid. For this purpose, DC-AC power converter is used. It is also known as inverter and constitutes the main component of solar farm. Step-up transformer is used to increase the voltage level up to the grid voltage level. Depending upon the power rating, the size and type of conductors are chosen to connect it to the grid line.

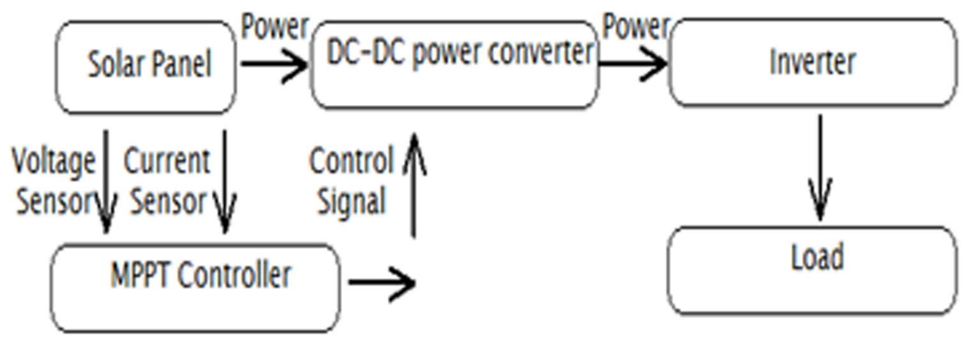

Figure 2: Block diagram of Solar Farm

Advantages of solar farms

1. It has no moving parts and hence maintenance is minimal.
2. It doesn't produce by-product or waste generated, except during manufacturing or dismantling.
3. It gives choice to the customer of buying green electricity and reduce reliance on scarce fossil fuels.

4. MPPT OF PV SYSTEM

To overcome the low energy conversion efficiency problem of PV module, optimization of PV system is required to get maximum possible output. For this purpose, MPPT controllers are used. Since seventies, number of MPPT control scheme like perturbation & observation, incremental conductance, fuzzy based MPPT, ANN based MPPT etc. have been elaborated. The choice of MPPT depends on the robustness of the system [12] [13]. For a particular load, maximum power point is a particular operating point, where the power is maximum and it depends on the load characteristics. Figure-3 is I-V characteristics and P-V characteristic of PV system. To obtain this MPP, an adaptive device MPPT with DC-DC converter is used between source and load [14]. Temperature and insolation also affects the operating characteristics as well as MPP of PV-system. So it is required that MPPT controller must be able to track new MPP with the variation of temperature and variation.

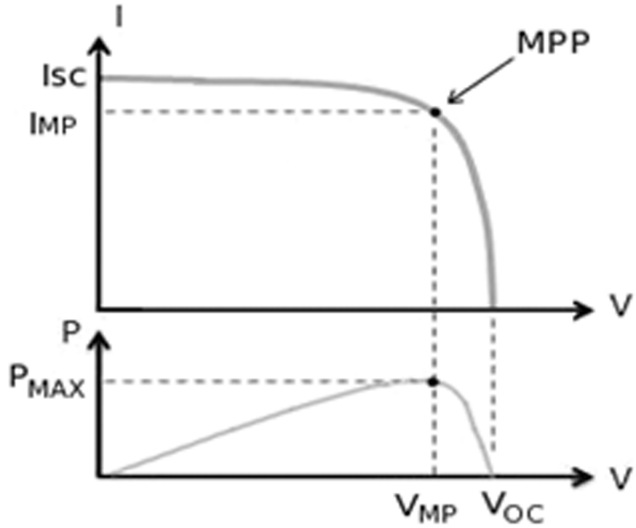

Figure 3: I-V and P-V characteristics of PV system

5. SIMULATION AND RESULTS

To carry out the objective of the work, following steps has been applied in MATLAB/Simulation:

- Design of Solar Cell with boost converter, MPPT and duty cycle control of boost converter and MLI design.
- Analysis under normal condition
- Analysis with fault

5.1. Design Of Solar Cell With Boost Converter, MPPT And Duty Cycle Control of Boost Converter And MLI Design:

To design the solar cell single diode model has been considered. The characteristic equations of single diode model are [15 [16]:

$$I = I_{lg} - I_{os} * \left[\exp\left\{ q * \frac{V + I * R_s}{A * k * T} \right\} - 1 \right] - \frac{V + I * R_s}{R_{sh}} \tag{3}$$

Where,

$$I_{os} = I_{or} * \left(\frac{T}{T_r} \right)^3 * \left[\exp\left\{ q * E_{go} * \frac{\frac{1}{T_r} - \frac{1}{T}}{A * k} \right\} \right] \tag{4}$$

$$I_{lg} = \{ I_{scr} + Ki(T - 25) \} * \tag{5}$$

I & V	Cell output current and voltage
Ios	Cell reverse saturation current
T	Cell temperature in Celsius
k	Botlzmann's constatnt, $1.38*10^{-19}$ J/K
Ki	S/C current temp coefficient at I_{scr}

q	Electron charge .1.6*10^{-23} C
λ	Solar irradiation in W/m^2
Iscr	Short circuit current at 25^0 Celsius
I_{lg}	Light – generated current
E_{go}	Band gap for silicon
A	Ideality factor
T_r	Reference temperature
I_{or}	Cell saturation current at Tr
R_{sh}	Shunt resistance
R_s	Series resistance

The characteristic equation of solar cell depends on number of cells in series and parallel. Experimentally it has been observed that current variation depends more on series resistance in comparison to shunt resistance [17].

$$I = Np * I\,\mathrm{lg} - Np * Ios * \left[\exp\left\{ q * \frac{\frac{V}{Ns} + I * \frac{Rs}{Np}}{A * k * T} \right\} - 1 \right] - \frac{V * \left(\frac{Np}{Ns}\right) + 1 * Rs}{Rsh} \tag{6}$$

Above equations have been analyzed in MATLAB using Simulink toolbox. In this work FL MPPT has been used to get maximum power from the solar cell. The proposed MPPT has two inputs as shown in Figure 4.

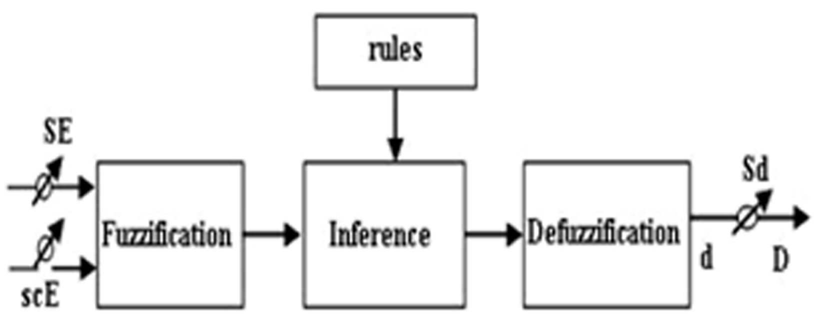

Figure 4: General diagram of Fuzzy Controller

E(k) and CE(k) are two input variables of FLC and at any sampled time k they can be defined as:

$$E(k) = \frac{Pph(k) - Pph(k-1)}{Vph(k) - Vph(k-1)} \tag{7}$$

$$CE(k) = E(k) - E(k-1) \tag{8}$$

In the above equation P_{ph} is the photovoltaic generator instant power. E(k) represents the load operation point with respect to the MPP and CE represents the direction of movement of MPP. Table 1 represents the rule base for Madnani's method used for fuzzy inference. Center of gravity method has been used for de-fuzzification. Output of FLC is duty cycle D and can be expresses as:

$$D = \frac{\sum_{j=1}^{n} \mu\left(Dj\right) - Dj}{\sum_{j=1}^{n} \mu\left(Dj\right)} \tag{9}$$

Table 1 indicates the control rules applied for MPPT. Five membership functions have been considered for C, CE and D. Membership functions C, CE and D are shown in Figure 5(a), 5(b) and 5(c) respectively. The output of FLC controls the duty cycle of boost converter

Table 1
MPPT control rules

E = dP/dV	*CE = del dP/dV*				
	NB	NS	ZE	PS	PB
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	NS	NS
PS	NS	NS	NS	ZE	ZE
PB	NB	NB	NB	ZE	ZE

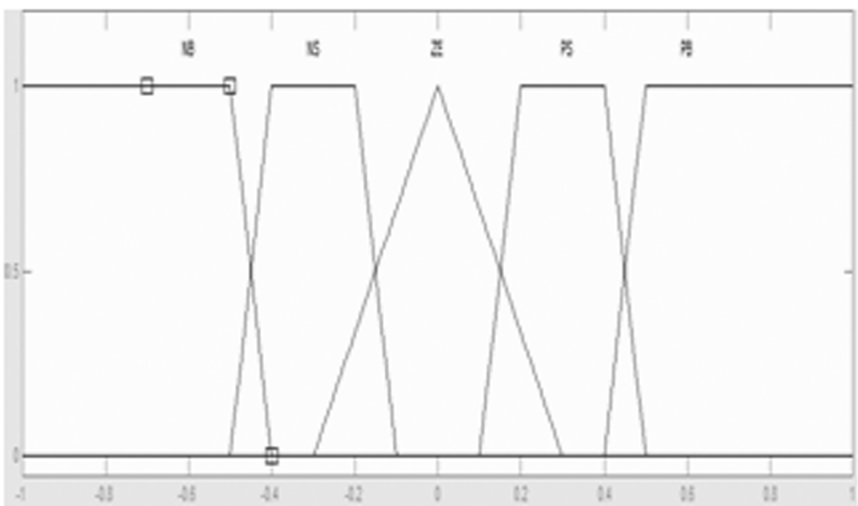

Figure 5: (a) Membership function of E (= dP/dV)

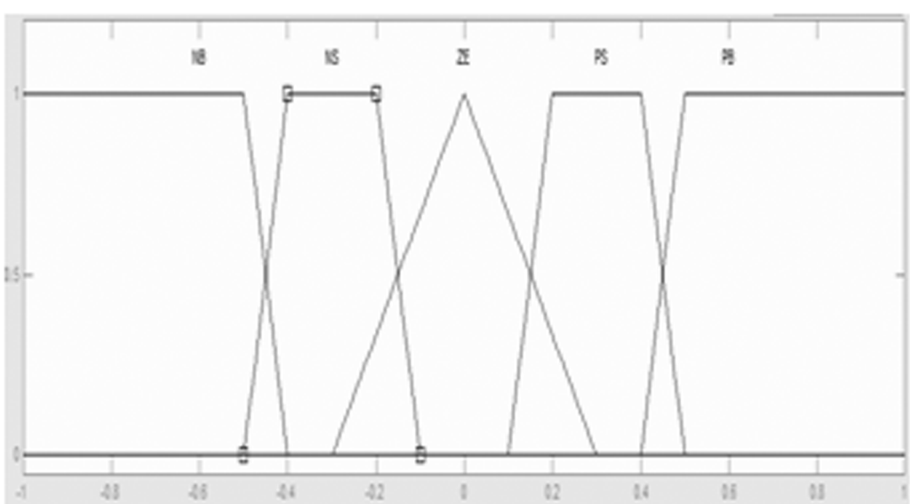

Figure 5: (b) Membership function of CE (= del. dP/dV)

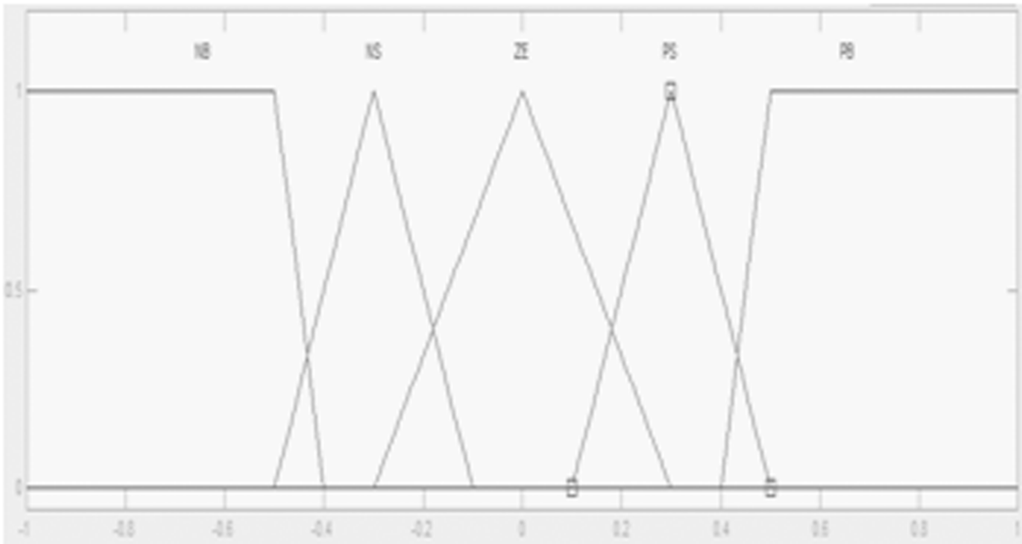

Figure 5: (c) Membership function of 'D'

Output power of boost converter after MPPT and control of duty cycle has been shown in Figure 6.

Figure 6: Boost Converter Power Output after MPPT

7 level Cascaded MLI configuration has been used to convert DC output to AC. The output of MLI has given to tap changing transformer through controlled voltage source to get sinusoidal voltage. MATLAB/Simulink schematic arrangement has been shown in Figure 7.

5.2. Analysis Under Normal Condition

Figure 8 shows the MATLAB/Simulink connection diagram used to measure power factor of the system. The output voltage of tap changing transformer of MLI is applied in quadrature with the system voltage Vs and output magnitude V_1 V_2 and V_3 are controlled according to the power factor of the system Vr_1, Vr_2 and Vr_3 are resultant system voltages. From Figure 9, as the magnitude of this quadrature voltage increases the angle between resultant voltages Vr_1, Vr_2 and Vr_3 and the system current decreases and hence the power factor of the network approaches to unity gradually. The simulation results of voltages and currents of all phases after injection of voltage V_3 has been shown in figure 10, the visual inspection of which lead to conclude that the power factor of the system has improved.

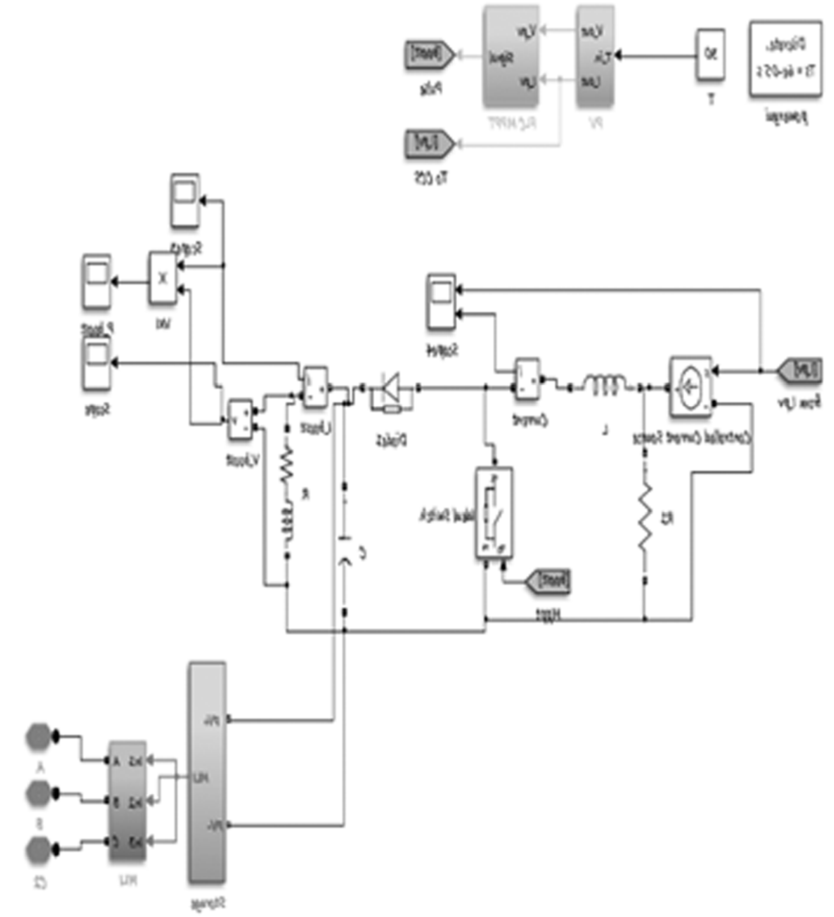

Figure 7 Simulink Model of Boost Converter with MPPT

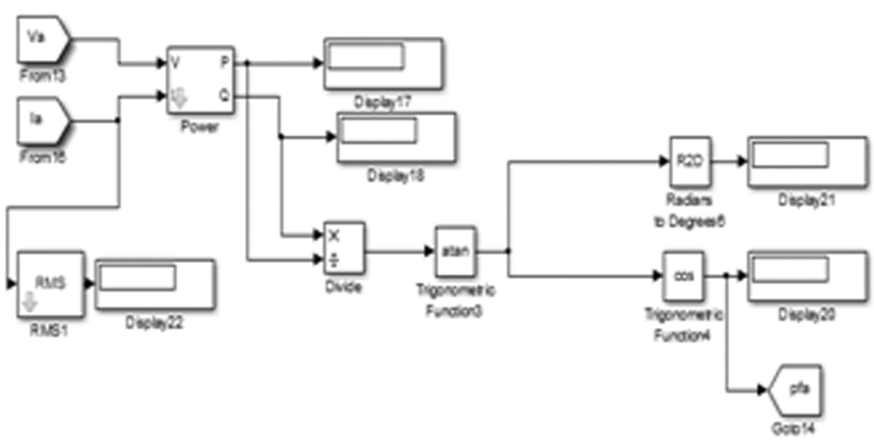

Figure 8: Simulink model of Power factor measurement

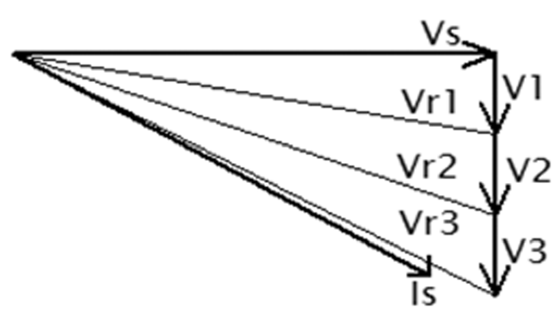

Figure 9: Effect of Quadrature voltage injection

Table 2
variation of power factor due to V1, V2 and V3.

Voltage provided by PV-Solar farm	*Power factor*
0	0.371
11kV	0.814
22KV	0.934
33KV	0.983

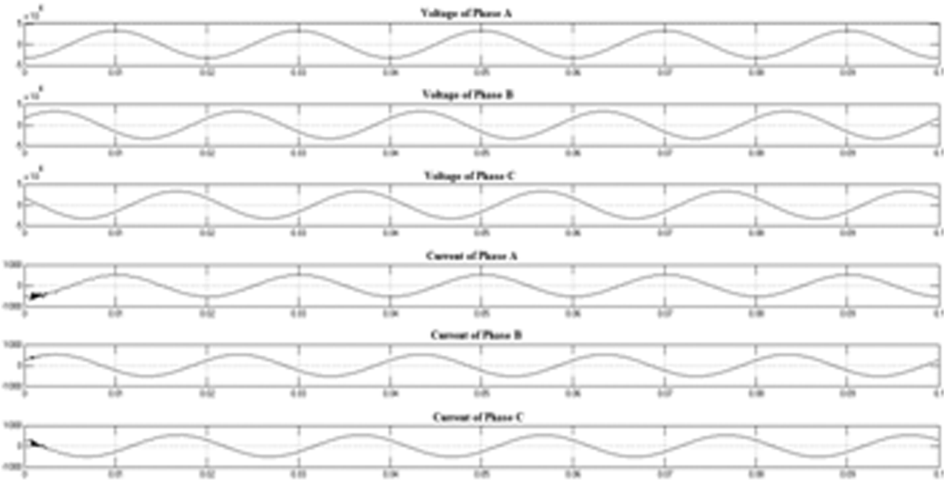

Figure 10: Effect of injection of quadrature voltage V_3

5.3. Analysis under fault

5.3.1. Without Compensation

As single line to ground fault is most common fault so in this work single line to ground fault has been considered. The fault has been applied in phase A. The waveforms of the voltage and current of all the phases of system under fault without compensation has been shown in figure 11.

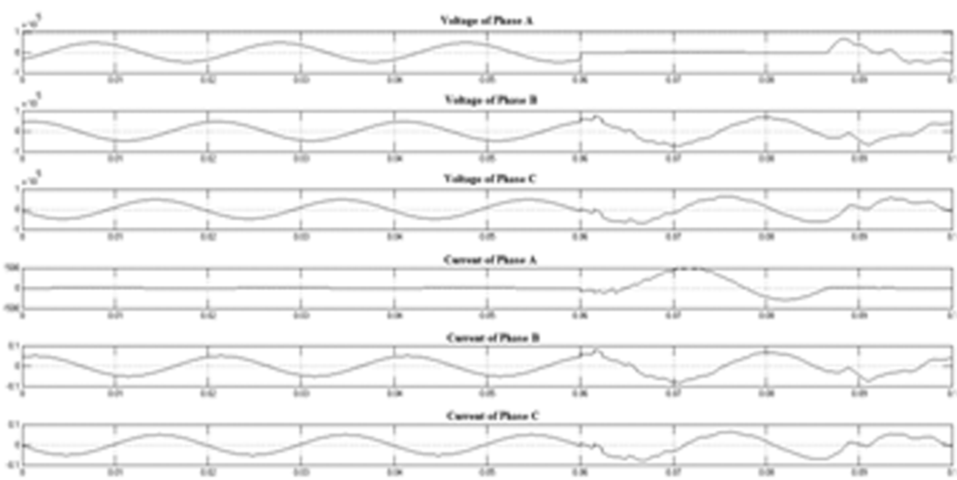

Figure 11: System response under fault - without compensation

5.3.2. With Compensation

Under fault condition the compensation has been to phase A provided by the designed solar farm. Figure 12 represents the system response under fault condition with compensation. The results show that the occurrence

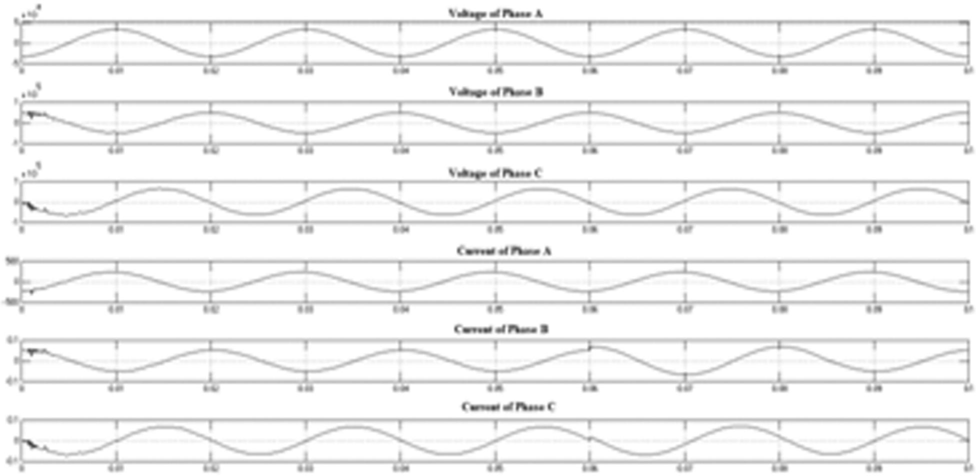

Figure 12: System response under fault-with compensation

of fault in phase A has no significant affect due to compensation provided by the designed solar farm but voltage and current get reduced in magnitude phase B and phase C. So by providing compensation to other phases by the designed solar farm the system performance can further be improved.

The complete MATALB/Simulation arrangement used for analysis has been shown in Figure 13.

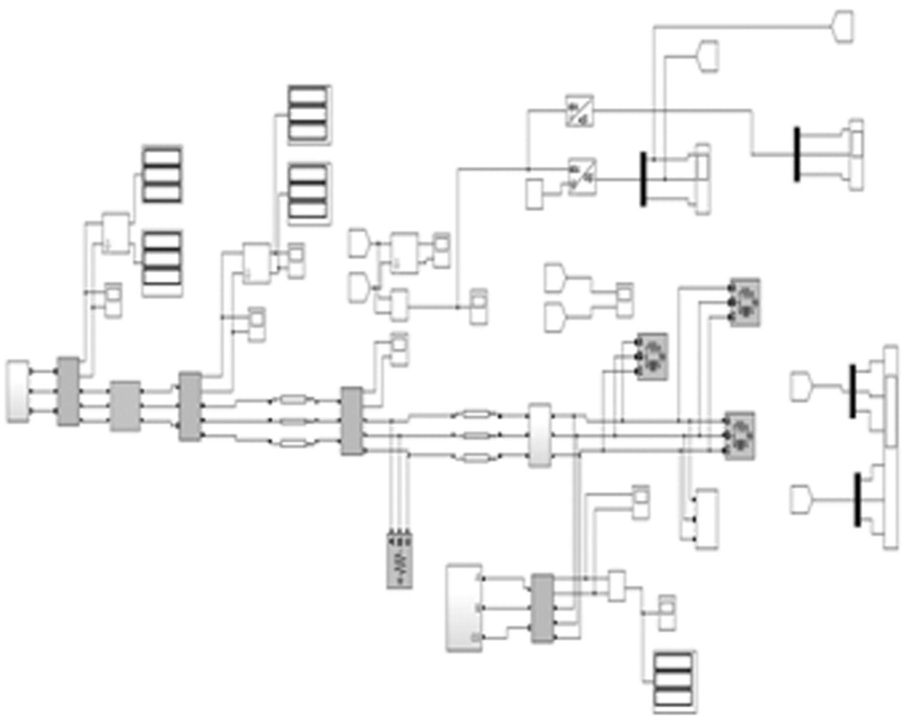

Figure 13: MATLAB/ Simulink model for analysis

6. CONCLUSION

With the advancements in power electronics and manufacturing technology, PV-based solar farm has become clean and cheap source of electric energy in recent few years. Solar farm can be utilized in standalone mode or in conjunction with the Grid to supply the load connected to the network. When it is used in conjunction with the main Grid then it can be used to supply the excess reactive power required by the load. In this way solar farm can reduce extra burden on the main Grid and improve the performance of complete network under normal switching load conditions. Also it can be used under fault condition to support the phases so that the effect of fault can be reduced and aid to the robustness of the network. In this work both the cases have been discussed with the help of MATLAB/Simulation and a robust system has been designed whose power factor has been improved by the reactive power injecting voltage in quadrature with the system voltage which is a method of reactive power compensation. It has also been shown by analysis and waveform that solar farm can be used to support the system in fault condition and hence performance of the system has been analyzed. From the simulation results it can be concluded that solar farm enhances the performance of the system and hence it has better performance than a Grid network system without solar farm compensation unit.

APPENDIX

Grid Voltage	=	11KV
Grid side Step-up transformer rating	=	200MVA, 50Hz, 11/110 KV
DC Power Output from Solar Farm	=	1.5 KVA
MLI side step-up transformer rating	=	25KVA, 50Hz, 0.3/110KV
V1, V2, V3	=	11KV, 22KV, 33KV
Load	=	110KV, 50Hz, 2KW, 500KVar

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