Behaviour of Photovoltaic System during Grid Disturbances

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Abstract— **Addition of many distribution resources in the existing network open up new challenges in power system protection. This paper deals with the transient behavior of grid connected PV system under various grid and climatic conditions. A study is carried out with detailed modeling of the system considering both dynamic and steady state responses. Impact of each system element on various conditions is analyzed. PV system along with distribution systems are modeled by using MATLAB/Simulink, such that faster simulation and better response is obtained.**

***Keywords*-Insolation/Irradiance, Phase locked Loop (PLL) frame transformation, Maximum power point (MPP), Matlab/Simulink, Photo-voltaic cell (PV), Controllers. Point of common coupling (PCC), Short circuit capacity (SCC), Standard Test Condition (STC).**

I. Introduction

INCREASING fear about global warming leads to a better international awareness in renewable energy sources. Many agreements have been signed by countries (e.g. Kyoto, Copenhagen and Durban) to reduce the global warming. IPCC reports on climate change (e.g. arctic snow melting) warned the global community on carbon foot print. Many countries have agreed to decrease their carbon foot print. In Copenhagen, India has made a commitment to reduce its emissions per unit of GDP 20 to 25% below 2005 levels by 2020 [1]. As we know 38 % of carbon is coming out from electricity generation.

Since GDP growth is linearly related with electricity production, so each year India has to increase the generation by 10% (current installation of 190 GW). Currently India is the third biggest consumer of coal and its growing deficit and increasing export tax in coal rich countries (e.g. Indonesia) leads to shut down of many thermal stations. Also 1unit of electricity produces 1kg of carbon, so it is difficult to go forward with coal based thermal plant, Government (MNRE) proposed a big project called [2] Jawaharlal Nehru national solar mission (JNNSM) at a cost of 19bn US$, to generate 20000 MW of grid connected solar energy before 2022, 1000 MW before 2013, and additional 3000 MW before 2017, using solar photovoltaic and solar thermal technique. It is planned to add power at 33 KV and above. Cost of electricity per unit from PV plant is decreasing year by year. Already its cost has gone below gas based plants. Considering growth of PV interface with the existing grid and response of PV plant is totally different from conventional synchronous machines. So a detailed study of transient response of PV plant is carried out in this paper, and based on the results, effect of system parameter for various disturbances are analyzed.

II. PV Cell Modelling

Since PV cells are P-N junction semiconductor devices, their V-I characteristics are shown in Fig. 1.

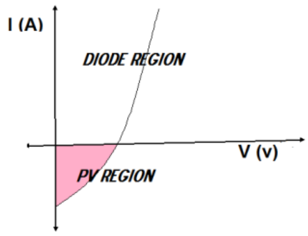

Fig. 1. Region of Operation of a Photovoltaic Cell

The above Fig. 1 shows that PV Cell has a nonlinear V-I characteristics, also, it is depends on irradiance, Temperature and other climatic condition. Most commonly PV is modeled as current source parallel with the diode (Fig. 2) with its internal resistances.

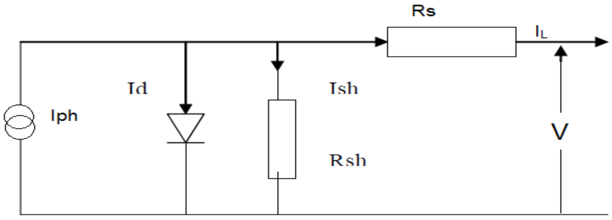

Fig. 2. Single Diode model

$$I_L = I_{ph} - I_o\left[e^{\left(\frac{V+I_L R_S}{V_T}\right)} - 1\right] - \left[\frac{V+I_L R_S}{R_{Sh}}\right] \quad (1)$$

Where

R_s – Series resistance (semi conductor resistance)

R_{sh}- Shunt resistance (due to recombination)

Id – Diode/Dark current

I_{ph} –Photo current,(proportional to irradiance)

V_T – Thermal voltage KT/q

I_0 – Reverse Saturation Current of the diode

There are some other important parameters of PV, called short circuit current (Isc – output current, when its PV terminals shorted (Fig 2)) and open circuit voltage (Voc – voltage at the output, when no load is connected). Some literature have proposed double diode model to represent PV Cell, but both the models uses many parameters (e.g. Rs, Rsh, I_{01}, I_{02}, I_{ph}, V_T) which are not available, because it is depends on the property of the material, and it is not given by manufacturer.

Semiconductor equations are derived from five carrier transport differential equations, which assume uniform doping and crystalline material. But this is not the case with practical module and thin film PV (which have p-i-n junction). So we need a model that using only the data given by manufacturer data sheet [3-6], also it must take care of change due to climatic condition (normally irradiance, Temperature and wind speed). Translation equations are proposed [3-4] to translate voltage and current from one condition to another condition. But it won't relate voltage with current. So the model given in the Literature [5-6] is used to represent the PV Cell.

$$I_L(V) = \alpha \cdot I_{max} \cdot \tau_i - \alpha \cdot I_{max} \cdot \tau_i \cdot e^{\left(\frac{V}{b\cdot(\gamma\cdot\alpha+1-\gamma)\cdot(V_{max}+\tau_v)} - \frac{1}{b}\right)} \qquad (2)$$

Where $\alpha = \frac{E_i}{E_{iN}}$; $I_{max} = \frac{I_{SC}}{1-e^{\left(-1/b\right)}}$; $\gamma = 1 - \frac{V_{min}}{V_{max}+\tau_v}$

Current and Voltage variation due to Temperature

$$\tau_i = 1 + \frac{TCi}{100} \cdot (T - T_N) \;\&\; \tau_v = TCV \cdot (T - T_N)$$

The equation (2) [5] is used to model the PV, all parameters in the above (2) is given in the manufacturer data sheet [7] at standard test condition (STC). Characteristic factor b is calculated[8] using data from STC and other performance condition is given in the data sheet. SANYO 215A panel is used to do the analysis.

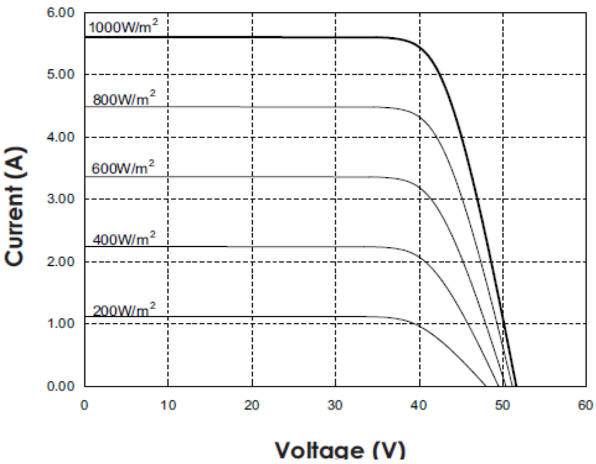

Fig.3. V-I charcateristics of SANYO 215A panel given in the maunfacturer data sheet

By comparing Fig. 3 & 4 we can say that the given equation exactly represent the PV characteristics, for different irradiance and temperature. From the equation (2) & Fig 5 PV will supply maximum power only at a particular cell voltage (or load), so we need an efficient MPPT (Maximum Power Point Tracking) to harvest maximum power from PV system, which acts as an important role in PV system dynamics during gird voltage disturbances and varying climatic conditions.

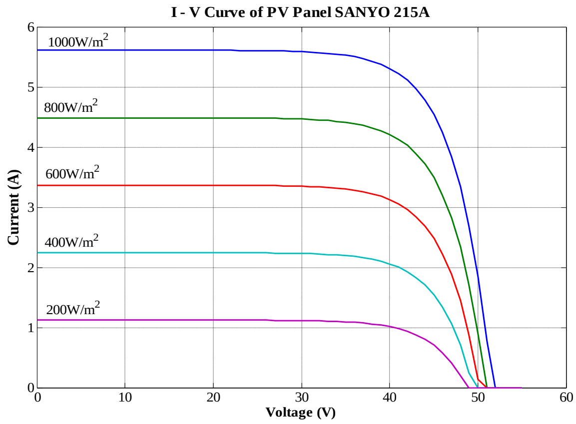

Fig . 4. V-I Curve obtained from equation (2) with b= 0.0769

. All input and translation equation uses cell temperature but we have only record of ambient temperature. So PV Cell temperature is found by using NOCT (Nominal operating cell temperature).

$$T_{cell} = T_{ampient} + \frac{(NOCT - 25^o)\times irradiance}{800} \qquad (3)$$

Here, all the analysis are done for $T_{cell} = 25^o$C

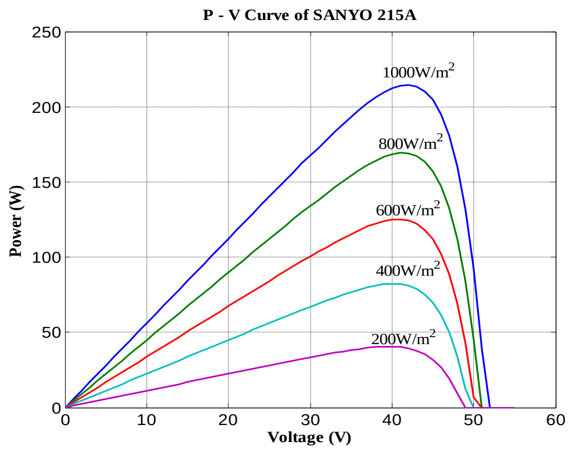

Fig. 5. Power generation from PV Cell with respect to voltage and irradiance

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III. PV System Design

Photovoltaic plant have many dynamic elements, and setting the parameter of those elements (e.g. MPPT, Inverter) acts as an important role in Transient behavior of PV System

A. *PV System Specification*

For the purpose of analysis, two PV systems with the capacity of 500kW each (2×500kW) as shown in the Fig.6 are modeled using SANYO 215A solar panel, with the switching frequency of 5kHz, feeding power to the 33kV distribution system. Current mode control [9-10] with synchronous reference frame based control is used to control the PV Plant.

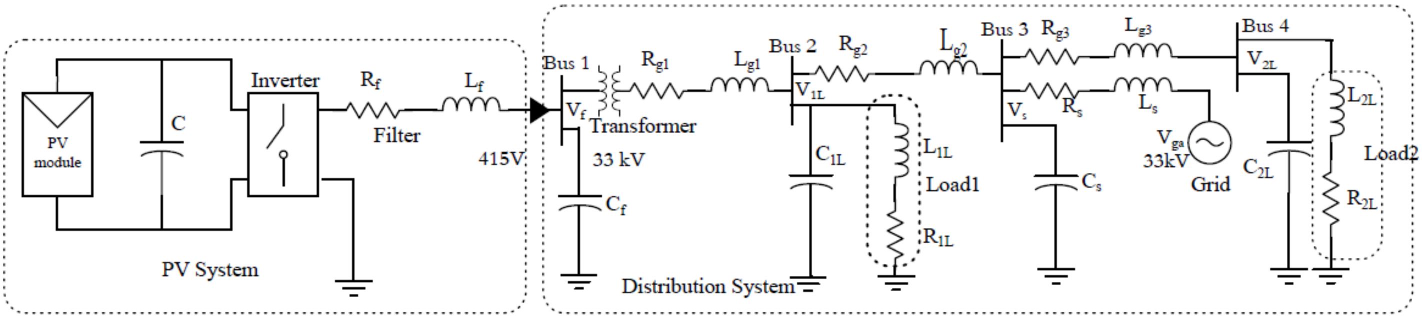

Fig. 6. Single Line Schematic Diagram of the photovoltaic system interfaced with Distribution Network

In megawatt PV plant, many panels can be connected in series to get high voltage, so there is no need of any boost/buck-boost stage. Here PV panels are directly connected to DC bus of the inverter. Delta Star transformer with the rating of 1.5MVA with voltage 415V (PV side)/ 33kV (grid side) is used to connect the PV system to the grid. Number of panels per string is determined by considering possible grid voltage and irradiance disturbance and PWM techniques employed. For the sake of simplicity sine triangle PWM is implemented. By considering above, 20 panels per string which produce maximum of 1026V at STC were connected in series. PV model is simulated using MATLAB/Simulink blocks without using any power system toolbox. This is done to speed up the simulation. Simulations are carried out with and without (average model) inverter, both the cases same response was observed. Since our aim is to study large disturbance, so harmonics injected by the system is not of interest.

B. MPPT (Maximum Powerpoint Tracking)

Many MPPT techniques are proposed [11]. P&O (Perturbation & Observation method) is used due to its simplicity and easy implementation. 0.1V perturbation with the time 2ms is used to accelerate the simulation speed. MPPT tracking range is set between 700 to 1026 V.

IV. PV System Control

Synchronizing the PV system to the grid needs information about certain grid parameters, these information's are obtained from PLL. Here synchronous reference frame (d & q axis) based control, where three phase quantity is translated into a rotating space vector is used to control the power flow. In this study grid voltage vector is aligned towards d axis. So aligning of current vector to the grid d axis ensures a unity power factor operation. Separate controllers are used to control active (Id) , reactive (Iq) power, and separate voltage controller is used to control the voltage across the inverter. PLL is used to track the gird frequency and voltage.

A. Phase Locked Loops (PLL)

To supply unity power factor current and to maintain synchronism with the grid, PV system needs grid angle, voltage and frequency, Synchronous reference frame PLL with moving average filter is implemented [13]. Moving average filter is used to eliminate 2nd harmonic negative sequence component as in eq 10. Dynamics of PLL have significant role in transient behavior of PV system. Because important parameters (V_{sd}, V_{sq}, sin(ρ), cos(ρ), ω) are obtained from PLL, which have significant influence in modulation index.

$$V_{sd} = \frac{3}{2}(V_{1m} - V_{2m}\cos(2\omega t + \phi_1 + \phi_2) \qquad (4)$$

$$V_{sq} = \frac{3}{2}(V_{2m}\sin(2\omega t + \phi_1 + \phi_2) \qquad (5)$$

The above equation derived by assuming PLL tracking positive sequence space vector.

Where

V_{1m} - Positive sequence component peak voltage
V_{2m} - Negative sequence component peak voltage
ϕ_1 - Angle between R phase voltage and its positive sequence component
ϕ_2 -Angle between R phase voltage and its negative sequence component

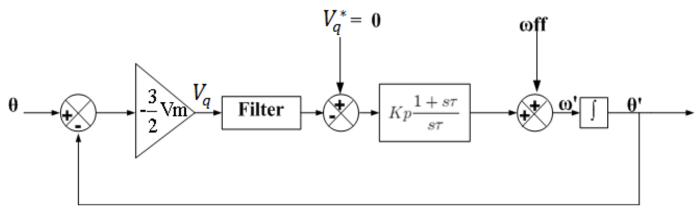

Fig. 10. Simplified Structure of SRF PLL with filter

B. Current Controllers

Controls the current injected to the grid, decoupled Id & Iq are used to simplify the MIMO system into two SISO system as in the eq 7.

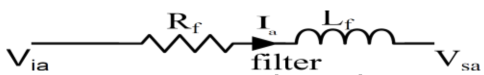

Fig.7. Inverter –Filter – Grid

$$\bar{V_i} - \bar{V_g} = R\bar{I_i} - L\frac{d\bar{I_i}}{dt} \qquad (6)$$

$$\bar{I_i} = I_\alpha + jI_\beta;\ \bar{V_i} = V_{i\alpha} + jV_{i\beta};\ \bar{V_g} = V_{s\alpha} + jV_{s\beta}$$

Where

$\bar{V_i}$ = Space vector of inverter output voltage
$\bar{V_s}$ = Space vector of supply voltage
$\bar{I_i}$ = Space vector of Inductor current

$$L_f\frac{d}{dt}\begin{vmatrix} I_d \\ I_q \end{vmatrix} = \begin{vmatrix} R & 0 \\ 0 & R \end{vmatrix}\begin{vmatrix} I_d \\ I_q \end{vmatrix} + \begin{vmatrix} V'_{id} \\ V'_{id} \end{vmatrix} \qquad (7)$$

$$V'_{id} = V_{id} + \omega L I_q - \bar{V}_s;\ V'_{iq} = V_{iq} - \omega L I_d$$

From the eq. 5 , filter inductance and resistance act as a plant for the current control loop as shown in the Fig. 7.Controller parameters are selected [12] such that current controller is faster than voltage controller. Inverter is modeled as a first order system with the bandwidth equal to, double that of switching frequency. Sampling time is used as a sensor time constant.

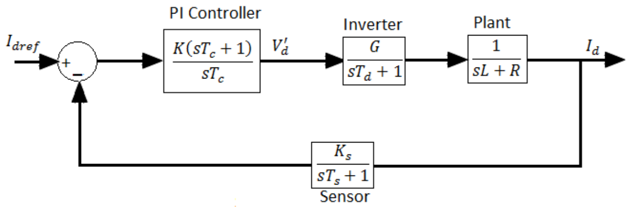

Fig. 8. Current controller block diagram

I_{dref} is calculated (eq. 8) using power balance, by neglecting inverter non idealites

$$I_{dref} = \frac{3V_{pv} I_{pv}}{2V_{sd}} \tag{8}$$

C. Capacitor Voltage Controller

PV is directly connected across DC bus capacitor, So Voltage across capacitor must be maintain constant to harvest maximum power from the PV, also to reduce output ripple and to ensure balanced output. Voltage is controlled by controlling the output current (as shown in the eq. (9))

$$I_{cap} = I_{pv} - \left(S^a I_a + S^b I_b + S^c I_c\right) \tag{9}$$

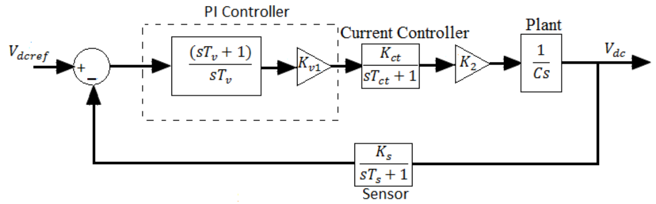

Fig. 9. Voltage Controller block diagram

Since full simulation is done by mathematical equations using Simulink blocks, all the possible voltage variation must be modeled. It is found that, capacitor voltage will vary due to, change in max power point (I_{pv}, V_{pv}) and output current (I_a, I_b, I_c). The first case taken into account by the voltage controller as shown in the Fig. 9 and later modeled either by injecting the capacitor current or using power balance in the above block diagram, as shown in Fig 8a.

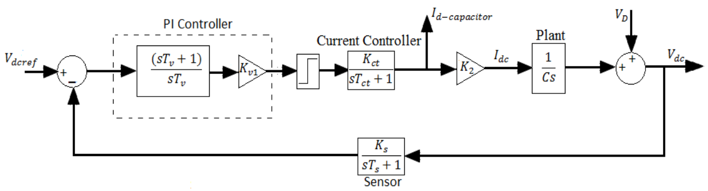

Fig. 9a. Implementation of Capacitor voltage control

V_D- Effect of change in capacitor voltage due to I_a, I_b, I_c

$$V_D = \frac{V_{pv} I_{pv} - V_{sd} I_d + V_{sq} I_q}{V_{pv} Cs} \tag{10}$$

So from the above, net current injected to the grid is equal to

$$I_d = I_{dref} - I_{d-capacitor} \tag{11}$$

$I_{d-capacitor}$ - Current injected into capacitor to maintain constant voltage.

V. Modeling of Full System

Overall system as shown in the Fig. 6.were divided into two parts.

1. Detailed modeling of Non linear PV system (415V), includes filter inductor, PV panel, Controllers and PLL.
2. Linear elements, which include Distribution system (33kV), filter capacitor, grid and load, were modeled in state variable form, so it can be easily implemented in state variable block of Simulink. This enable us to use the same model for large distribution network by just altering A, B, C, D parameter. With improved simulation performance.

A. Photovoltaic system dynamic equation

PV systems have many dynamic elements, which are already discussed in the previous sections. The dynamic equation of DC bus capacitor is,

$$C\frac{dV_{dc}}{dt} = I_{pv} - \left(S^a I_a + S^b I_b + S^c I_c\right) \tag{12}$$

In the above equation I_{pv} is a non linear function of V_{dc}. Linearization of above model won't be suitable for large signal disturbances, so here detailed modelling of PV system is done using Simulink blocks.

B. Distribution system

Distribution system [14] includes filter capacitor of PV system which translated from 415 V side to 33kV side, transformer equivalent leakage reactance with respect to high voltage side, distribution line, Load and short circuit MVA of the substation. Loads are provided with reactive power compensation. Gird voltage and injected PV system currents act as a input to the system.

State equation of distribution system

$$\dot{x} = Ax + Bu \text{ (Sate Equation)} \tag{13}$$

$$y = Cx + Du \text{ (Output Equation)}$$

From Fig 6. Sate variable matrix A=

$$\begin{bmatrix} 0 & 0 & 0 & 0 & -1/C_f & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/C_{1L} & -1/C_{1L} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/C_s & -1/C_s & -1/C_s \\ 0 & 0 & 0 & 0 & 0 & 0 & 1/C_{2L} & 0 \\ 1/L_{g1} & -1/L_{g1} & 0 & 0 & -R_{g1}/L_{g1} & 0 & 0 & 0 \\ 0 & 1/L_{g2} & -1/L_{g2} & 0 & 0 & -R_{g2}/L_{g2} & 0 & 0 \\ 0 & 0 & 1/L_{g3} & -1/L_{g3} & 0 & 0 & -R_{g3}/L_{g3} & 0 \\ 0 & 0 & 1/L_s & 0 & 0 & 0 & 0 & -R_s/L_s \end{bmatrix}$$

$$x = \begin{bmatrix} V_f \\ V_{1L} \\ V_s \\ V_{2L} \\ I_{g1} \\ I_{g2} \\ I_{g3} \\ I_s \end{bmatrix} \quad B = \begin{bmatrix} 1/C_f & 0 & 0 & 0 \\ 0 & -1/C_{1L} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -1/C_{2L} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/L_s \end{bmatrix} \quad u = \begin{bmatrix} I_a \\ I_{1L} \\ I_{2L} \\ V_{sg} \end{bmatrix}$$

$$C = [I]_{8\times 8} \;\&\; D = [0]_{8\times 4}$$

Load Model

Linear RL load with reactive power compensation is modeled; it takes bus voltage as a input and it inject (output) the current to the distribution network.

VI. SIMULATION

The modeled system is simulated for various grid disturbances (e.g. 3phase fault, voltage and frequency disturbances) and environmental conditions (e.g. irradiance and temperature).

A. System implementation

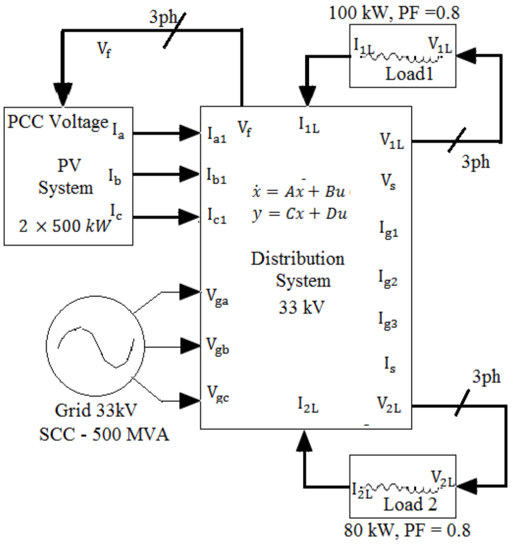

Fig. 11. System implementation using MATLAB- Simulink

System in eq. (13) is implemented as shown in Fig. 11, The PV system is modeled such that, it will inject current based on voltage at the PCC and load inject current (-ve) to the distribution system based on bus voltage. The above way of implementation is faster, may be useful for any number of distribution system, by just changing A, B parameters in eq.13. Generalized program can be written in MATLAB, which creates state matrix, and automatically load data into Matlab workspace. For fault analysis, fault can be created by separating the fault line from A matrix and it is implemented by transfer function, where current is the input and voltage as the output, by changing the voltage output of the line model, any type of fault can be easily simulated. Many cases are simulated, due to space constrain only four cases are discussed here.

B. Case1

Grid voltage changed from 1pu to 0.85pu. In this case current controller and PLL acts as a significant role in deciding dynamics of the system. Fig 12 shows response of each element during voltage disturbances. For voltage disturbances MPPT and voltage controller have less effect as shown in Fig 12a & 12b and Fig 12 d & 13 shows effect of PLL and current controller dynamics. PV system tracks the grid voltage within one cycle, since there is not much influence of MPPT, response is quite faster.

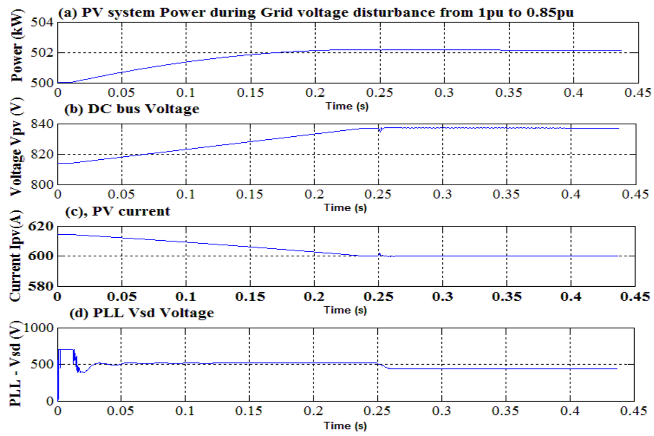

Fig 12. Response of PV system elements, during grid voltage disturbances

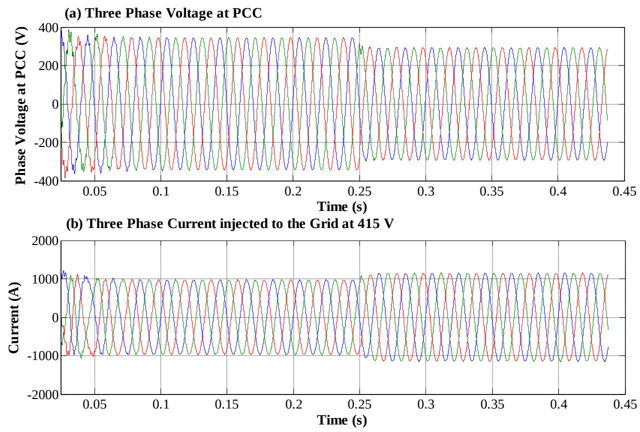

Fig. 13. Effect of Current controller & PLL for Voltage disturbances

C. Case 2

Change in irradiance from 1000W/m^2 to 500W/m^2, Fig 14 shows the response of system elements for climatic disturbances. PLL have no influence on irradiance disturbances, but all other dynamic elements have impact on system response. Since current reference is changing, so current controller have significant role. MPPT and voltage controller also have significant impact on dynamics as shown in Fig 14b

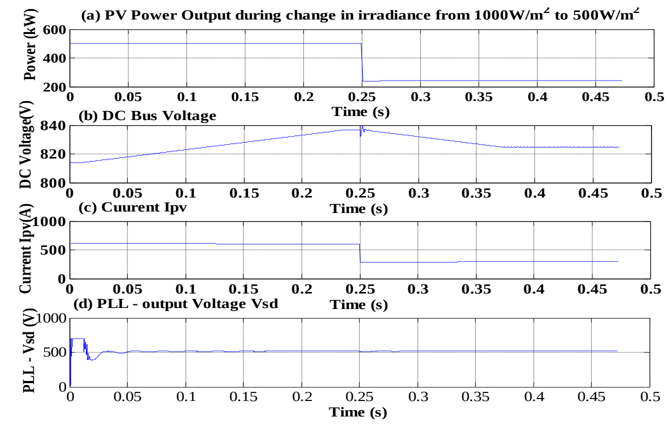

Fig. 14. Response of PV system for change in irradiance

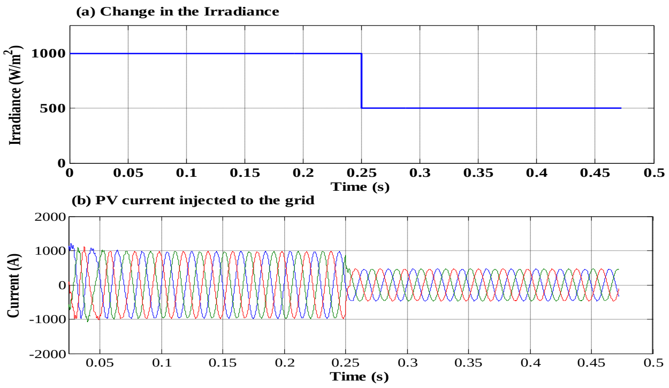

Fig. 15. PV system current injection during irradiance disturbance

D. *Case 3*

Three phase bolted fault at the middle of line 1 (between bus 1 & 2 in Fig. 6). As shown in the Fig. 16, during bolted fault, other than MPPT remaining all elements has impact on system response. To protect the system, short circuit current is limited between 1.5 to 2pu based on the system design. So short circuit current is completely dependent on system design. It is observed that saturation block in the current (both Id & Iq) and voltage controller have very significant role in system short circuit response

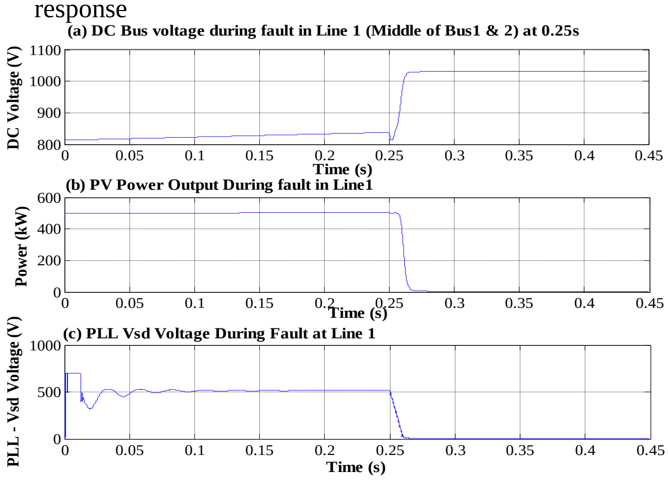

Fig. 16. Response of PV system for fault in Line 1

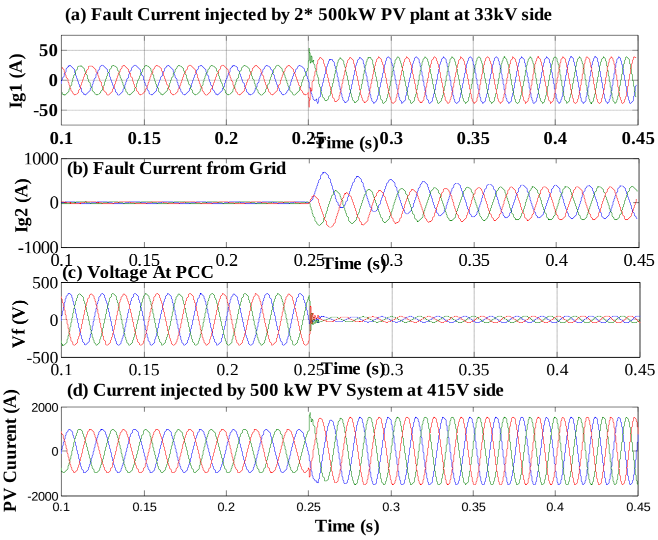

Fig. 17. Grid & PV system current contribution during fault in Line 1

The important effect of fault in the vicinity of PV system is, an increase in the capacitor voltage as shown in the Fig 16a, because fault needs reactive power but PV supplies active power, this leads to increase in capacitor voltage that intern leads to decrement in PV output power. So PV system settles at some equilibrium point as shown in the Fig 16 b. Since fault had happen relatively for from substation, PV system contribution for the fault in this case is around 10 %. For larger PV system contribution will gradually increase, So all relay co-ordination must take PV response into consideration.

E. *Case 4*

Three phase bolted fault at the middle of line 3 (between bus 3 & 4 in Fig. 6). Since fault point is near to the substation, grid supplies very high fault current, but PV supplies relatively less (less than 0.4 %) fault current. But both case D & E, PV supplies same current, but case E have less influence compare to case D. Since fault is quite far from PV station, PCC have around 0.5pu voltage. This helps PV to supply full 1MW to the system as shown in the Fig. 18.

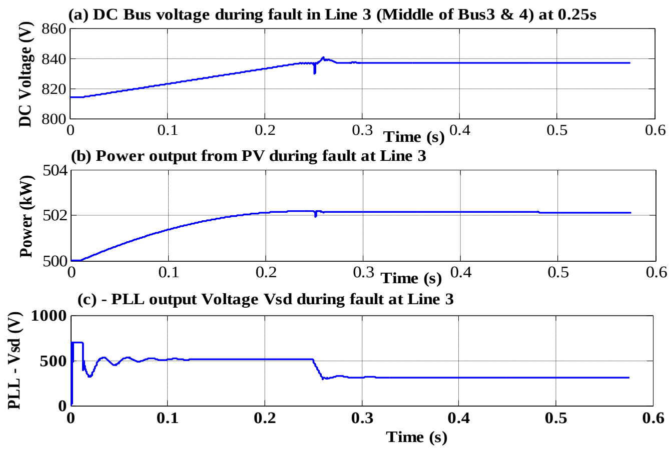

Fig. 18. PV system response, for fault in Line 3

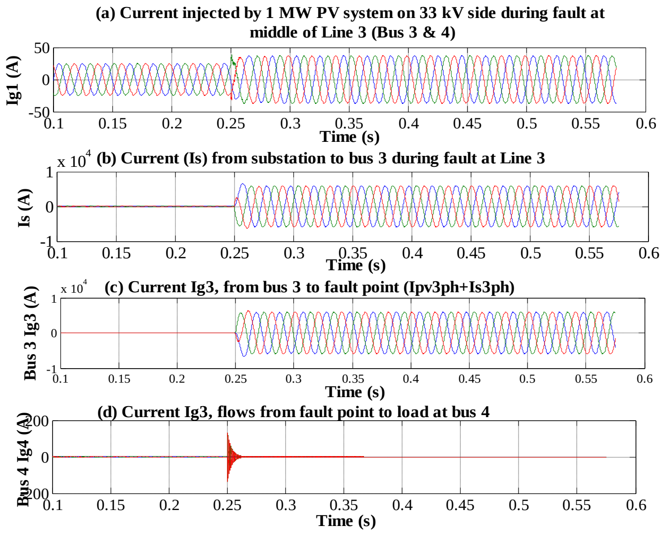

Fig. 19. Grid & PV system current contribution during fault in Line 3

Fig. 19a & b shows short circuit current contribution of PV system and grid respectively. Fig 19d shows effect of reactive power (R-L) load in bus 4.

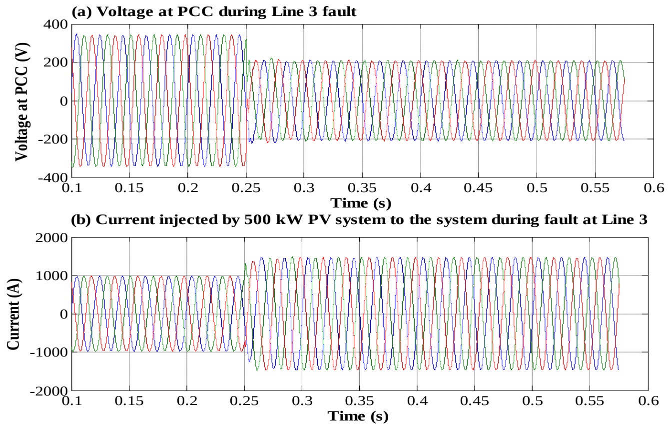

Fig. 20. PCC voltage and PV system (500kW) current injection during fault in line 3

F. Observation

Transient response of PV system is fully dependent on system (e.g. controller) design and liming value of controllers. It found that faster current controllers have less overshoot than slower ones. It is very difficult to generalize the transient behavior of a PV system. In steady state, all PV systems have the same response. Therefore there is a need for standardization of the PV systems.

VII. Conclusion

In this paper full PV system is modeled using mathematical blocks without using any specialized software, this leads to better simulation performance. Since manufacturer data sheet based PV model is implemented, this gives very practical way of modeling the available PV panel. PV systems are modeled by using Simulink blocks, and interfaced with the distribution system, by the above method. Detailed study on PV system parameters were carried out and fault contribution of PV system is discussed. Irrespective of the location of fault, PV system supplies almost same fault current, due to its maximum inverter current limit. Normally short circuit currents are varying between 1.5 to two times of rated current [15]. Dynamics of the system is fully dependent on the parameter selection of the system. As per standard IEEE 1547, PV system supplies fault for a limited period of time, for bolted fault near to PV system, PV will get disconnected before or just after reaching the steady state. Therefore there is a need to study the transient behaviour for high penetrated PV systems and there is a need for standardization of PV system design including selection of controller parameters. This will be very important for micro grid based applications.

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