INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN 2278 – 0211 (Online)

Stability Enhancement of Three Phase Grid Connected Photovoltaic System Using Partial Feedback Linearization Scheme

M. B. Maunigasri
P.G. Scholar, Department of Electrical and Electronics, SNS College of Technology, Coimbatore, India
Dr. R. Subramanian
Professor, Department of Electrical and Electronics, SNS College of Technology, Coimbatore, India

Abstract:
This project presents a stabilization scheme for a three-phase grid-connected photovoltaic (PV) system to control the current injected into the grid and dc-link voltage to extract maximum power from photovoltaic (PV) units. The scheme is achieved mainly based on the design of a controller using a partial feedback linearizing approach of feedback linearization where the stabilization of the scheme is ensured by considering uncertainties within the PV system mode. The performance of the stability enhancement is evaluated on a three-phase grid-connected PV system in terms of delivering maximum power under changes in atmospheric conditions. In the grid connected PV system the control objectives are met by a strategy using a pulse width modulation (PWM) scheme based on two cascaded control loops. The two cascaded control loops consist of an outer voltage control loop to settle the PV array at the Maximum Power Point (MPP) and an inner current control loop to establish the duty ratio for the generation of a sinusoidal output current which is in phase with the grid voltage.

Keywords: *Three-phase grid connected Photovoltaic (PV) system, Boost Converter, MPPT, Linear and Non-linear controller, PWM technique, VSI*

1. Introduction

The utilization of the grid connected Photovoltaic (PV) system can be increased being pursued as a supplement and an alternative to the conventional method of power generation to meet the energy demand. The major concentration of integrating PV system into the grid is stochastic behaviors of solar irradiations and interfacing of inverters with the grid in [1]. The Maximum power point tracking (MPPT) technique is widely used to extract maximum power from the PV system that is delivered to the grid through the inverter in [2]. Interconnections among the PV modules within a shaded PV field can affect the extraction of maximum power. So that efficient control schemes are essential to operate with the environmental changes for the extraction of maximum power from the PV units. Inverters interfacing PV modules with the grid perform two major tasks—one is to ensure that PV modules are operated at maximum power point (MPP), and the second ones is to inject a sinusoidal current into the grid in [3]

In a grid-connected PV system, the control objectives is met by a strategy using a pulse width modulation (PWM) scheme based on two cascaded control loops. The two cascaded control loops consist of an outer voltage control loop to settle the PV array at the MPP, and an inner current control loop to establish the duty ratio for the generation of a sinusoidal output current is in phase with the grid voltage. Linear controllers such as proportional integral (PI), hysteresis, and model predictive controllers are presented in which provide satisfactory operation over a fixed operating points as the system is linearized at an equilibrium point. The PI current control scheme is used to keep the output current as sinusoidal and to have fast dynamic responses under rapidly changing atmospheric condition and to maintain the power factor at the unity.

Grid-connected PV systems are nonlinear systems where most of the nonlinearities occur due to the intermittency of sunlight and the switching functions of converters and inverters. To ensure the operation of a grid-connected PV system over a wide range of operating points, the design and implementation of a nonlinear controller is important. For a non-linear PV system, the linear controller affect the electrical characteristics of the PV source are time varying, the system is not linearizable around a unique operating point or trajectory to achieve a good performance over a wide variation in atmospheric conditions.

Feedback linearization has been increasingly used for non- linear controller design. It transforms the nonlinear system into a fully or partly linear equivalent by canceling nonlinearities in [7]. A feedback linearizing technique was first proposed in for PV applications where a superfluous complex model of the inverter is considered to design the controller. To overcome the complexity, a simple and consistent inverter model is used and a feedback linearization technique is employed to operate the PV system at MPP in [9]. A feedback linearizing controller is designed by considering the dc-link voltage and quadrature-axis grid current as output functions.

Power-balance relationships are considered to express the dynamics of the voltage across the dc-link capacitor. However, this relationship cannot capture nonlinearities cannot capture the nonlinear switching functions between inverter input and output; to accurately represent a grid-connected PV system but it is essential to consider these switching actions. The current relationship between the input and output of the inverter can be written in terms of switching functions rather than the power balance equation. Therefore the voltage dynamics of the dc-link capacitor include nonlinearities due to the switching actions of the inverter. The inclusion of these nonlinearities in the model will improve the accuracy; however, the grid-connected PV system will be partially, rather than exactly linearized in [10].
In the design of both linear and nonlinear controllers for grid-connected PV systems, most of the difficulties are from the analytical complexity of the dynamic model of a PV system, which on another hand exhibits a nonlinear parametric dependence on the PV array current–voltage characteristics varying with the irradiation and temperature levels and, on the other, a sinusoidal time dependence due to the grid connection of PV systems. These difficulties may lead to the some barriers in developing a meaningful and realistic mathematical model. The mismatch between the mathematical model and true system may lead to serious stability problems for the system. Therefore, the designs of robust control strategies that consider the model uncertainties are of great importance to design nonlinear controllers.

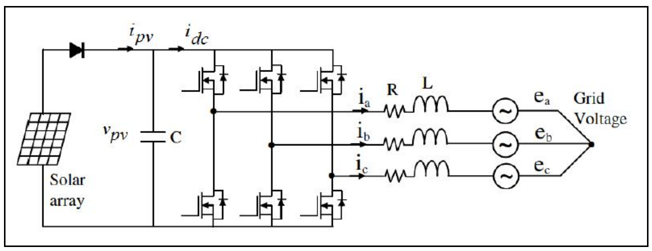

Figure 1: Overall Diagram of the Three-Phase Grid Connected PV System

The feedback linearization technique is widely used in the design of nonlinear controllers for the three-phase grid connected PV system, this paper proposed the extension of the partial feedback linearizing scheme, that is by considering uncertainties within the PV system model. In this paper, matching conditions are used to model the uncertainties in PV systems for given upper bounds on the modeling error, which include parametric and state-dependent uncertainties. These uncertainties are bounded in such a way that the proposed controller can guarantee the stability and enhance the performance of all possible perturbations within the given upper bounds of the modeling errors of nonlinear PV systems. The effectiveness of the proposed controller is tested and compared with that of a partial feedback linearizing controller without uncertainties with the changes in atmospheric conditions

2. Photovoltaic System Designing

The PV cell is the p-n junction diode which converts the light energy into electricity. Figure 2 shows the solar cell consist of an light generated current source, diode(D), shunt resistance *RSH* and the series resistance *RS*.

$$I_0 = I_{sr}\left[\left(\frac{T}{T_r}\right)^3\right] exp\left(\frac{qE_{gv}}{BK}\left\{\frac{1}{T_r}-\frac{1}{T}\right\}\right) \quad (1)$$

Where $I_0$is the dark saturation current, I0r is the saturation current at Tr, *q* is the charge of an electron, *A* and *B* is the diode quality (Ideality) factor whose value is between 1to 5, *k* is the Boltzmann constant, *T* is the absolute temperature in Kelvin, and *Egv* is the band gap energy of the semiconductor used in the cell,

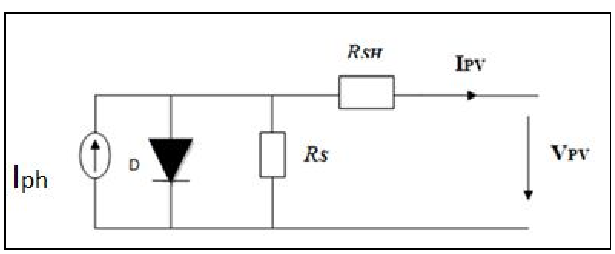

Figure 2: Equivalent Circuit of the PV Cell

The light generated current that is depend on the solar intensity that is given as

$$I_{ph} = [I_{scr} + K_i[T-298]]\,{}^{\lambda}/_{1000} \quad (2)$$

Where I_{ph} is the light generated current, $I_{scr}$is the Short circuit current at 25 deg. C, Tis the PV cell temperature, λ is the solar intensity.

The output voltage of the PV cell is given by

$$V_{pv} = \left[\frac{N_s ATK}{q}\right] \ln\left[\frac{N_p I_{ph} - I_{pv} + N_p I_0}{I_0}\right] - I_{ph} R_S \qquad (3)$$

Where N_s and N_p are the number of cell in series and the number of panel in the parallel and if the the value of the N_s and N_p can be varied, then the PV voltage and current can be varied. R_S and R_{Sh} is the series and shunt resistance of the PV cell. *RS* is the resistance offered by the contacts andthe bulk semiconductor material of the solar cell. The shunt resistance *RSH* is related to the non -ideal nature of the p–n junction andthe presence of impurities near the edges of the cell that provide a short-circuit patharound the junction. The output current of the PV cell can be written as,

$$I_{PV} = N_p I_{ph} - N_S I_0 \left[exp\left[\frac{q[V_{pv} + I_{ph} R_S]}{N_s ATK}\right] - 1\right] \qquad (4)$$

3. Maximum Power Point Tracking (MPPT) Technique

The MPPT technique is used to track the maximum power from the PV panel under climatic changing condition. The PV cell, V-I characteristics is not a linear one because it will with respect to the solar intensity and the temperature. The whole PV unit can operate at the maximum efficiency and maximum power at one point, at that point on the V-I & P-V curve is called as the Maximum Power Point (MPP). Then the location of the MPP can be maintained or tracked by using a technique called Maximum Power Point Tracking (MPPT). There are many MPPT techniques used in the PV system. But in this paper the Perturb &Observe (P&O) technique are choosing.

The P&O algorithms operate by periodically perturbing (i.e. incrementing or decrementing) the array terminal voltage or current and comparing the PV output power with that of the previous perturbation cycle. If the PV module operating voltage changes and power increases (*dP/dVPV*>0), the control system moves the PV array operating point in that direction; otherwise the operating point is moved in the opposite direction. In the next perturbation cycle the process is continues in the same way.

In this method, a small perturbation is injected to the system and if the output power increases, a perturbation with the same direction will be injected to the system and if the output power decreases, the next injected perturbation will be in the opposite direction.

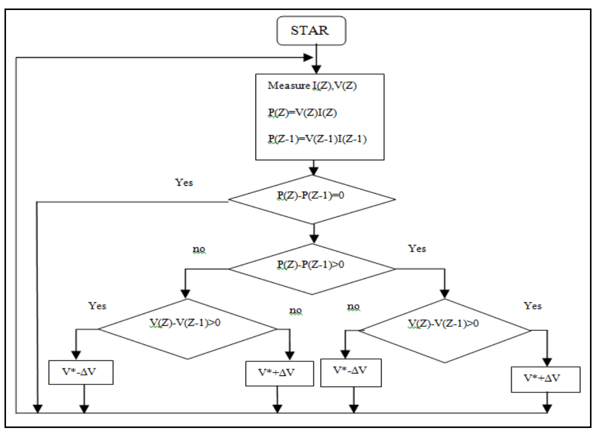

Figure 3: P&O Algorithm Flochart

4. Controller Design

The model of the three-phase grid connected PV system can be designed by using the Multi Input Multi Output (MIMO) non-linear system. Then the equation of the system can be written as,

$$\begin{aligned} \dot{x} &= f(x) + g_1(x)u_1 + g_2(x)u_2 \\ y_1 &= h_1(x), \\ y_2 &= h_2(x) \end{aligned} \qquad (5)$$

Where,

$$x = \begin{bmatrix} I_d \\ I_q \\ V_{pv} \end{bmatrix},$$

$$f(x) = \begin{bmatrix} \frac{R}{L} I_d + \omega I_q - \frac{E_d}{L} \\ -\omega I_d - \frac{R}{L} I_q - \frac{E_q}{L} \\ \frac{1}{C} I_{pv} \end{bmatrix},$$

$$g(x) = \begin{bmatrix} \frac{V_{pv}}{L} & 0 \\ 0 & \frac{V_{pv}}{L} \\ -\frac{I_d}{C} & -\frac{I_q}{C} \end{bmatrix},$$

$$u = \begin{bmatrix} K_d \\ K_q \end{bmatrix},$$

$$y = \begin{bmatrix} I_d \\ V_{pv} \end{bmatrix}$$

In a normal PV system, the operation of the PV cell can be changed with respect to the solar intensity and temperature. Due to this chages in atmosphric condition the output voltage, power and current of the PV cell can be varied. In this paper uncertainities are considered in the controller. The PV generation can be depend on solar intensity So that it can considered as a uncertainities and then other uncertainities is the system parameter.The uncertainities is added in the f(x) and the g(x). then the equation for the system is given as,

$$\dot{x} = [f(x) + \Delta f(x)] + [g_1(x) + \Delta g_1(x)]u + [[g_2(x) + \Delta g_2(x)]u_2]$$
$$Y_1 = h_1(x)$$
$$y_2 = h_2(x) \qquad (6)$$

Where

$$\Delta f(x) = \begin{bmatrix} \Delta f_1(x) \\ \Delta f_2(x) \\ \Delta f_3(x) \end{bmatrix} \quad \text{and}$$

$$\Delta g(x) = \begin{bmatrix} \Delta g_{11}(x) & 0 \\ 0 & \Delta g_{22}(x) \\ \Delta g_{31}(x) & \Delta g_{32}(x) \end{bmatrix}$$

The modelling uncertainities is used to attain the controller objective of the system. To attainthe control objective of the system, the uncertainities and the locationof the parameter must satisfy the following condition,

$$\Delta f(x) \,\&\, \Delta g(x) \in \text{span}\big(g(x)\big) \qquad (7)$$

The above condition is said to be the matching condition. If the above condition is satisied and then the following condition is true,

$$\omega \geq r = \rho \qquad (8)$$

From the above equation, **ω** is the relative degree of the uncertainities of Δg(x), **r** is the relative degree of the normal system which is equal to 2, and **ρ** is the relative degree off the uncertainity Δf(x).
To match the uncertainties to the PV system model, the relative degree value of the uncertainty Δ*f(x)* should be 2 as it needs to equal to the relative degree of the nominal system which is 2. The relative degree of the uncertainty Δ*f(x)* can be calculated as,

$$L_{\Delta f} L_f^{1-1} h_1(x) = \Delta f_1$$
$$L_{\Delta f} L_f^{1-1} h_2(x) = \Delta f_3 \qquad (9)$$

If the relative degree of Δf(x) corresponding to the output h_1 and h_2 is 1, then total relative degree of the Δf(x) is 2, it will happen when Δf1 and Δf3 is not equal to zero.

To match the uncertainty $\Delta g(x)$to the normalPVsystem, the relative degree of $\Delta g(x)$should be equal to or greater than the relative degree of the nominal system and will be 2 if following conditions hold,

$$L_{\Delta g} L_f^{1-1} h_1(x) = \Delta g_{11} \neq 0$$
$$L_{\Delta g} L_f^{1-1} h_2(x) = \Delta g_{31} + \Delta g_{32} \neq 0 \qquad (10)$$

Where $\Delta g11$ must not be zero and either $\Delta g31$ or $\Delta g32$ can be zero, to match the uncertainty with the structure of the PV system.
The uncertainty modeling has the upper bond of the uncertainty. To design the controller the upper bond of the uncertainty is considering. In this paper the maximum change in system parameter is considered as 40% and the changes in environmental condition is considered as 60%, then the $\Delta f(x)$ can be written as,

$$\Delta f(x) = \begin{bmatrix} -0.00025\frac{R}{L}I_d + 0.8\omega I_d - 0.25\frac{E_d}{L} \\ -0.38\omega I_d - 0.048\frac{R}{L}I_Q - 0.25\frac{E_Q}{L} \\ 0.15\frac{1}{C}I_{PV} \end{bmatrix} \text{ and}$$

$$\Delta g(x) = \begin{bmatrix} 0.20\frac{V_{pv}}{L} & 0 \\ 0 & 0.20\frac{V_{pv}}{L} \\ -0.10\frac{I_d}{C} & -0.16\frac{I_q}{C} \end{bmatrix}$$

The uncertainty modeling is considered in the controller design, and then the robust stabilization is achieved. The partial feedback linearization scheme for the system with uncertainty can be written as,

$$\hat{Z}_1 = h_1(x) = I_q$$
$$\hat{Z}_2 = h_2(x) = V_{pv} \qquad (11)$$

Where,

$$\hat{Z}_1 = \frac{\partial h_1(x)}{\partial x}\dot{x}$$
$$\hat{Z}_2 = \frac{\partial h_2(x)}{\partial x}\dot{x} \qquad (12)$$

Then,

$$\hat{Z}_1 = L_f h_1(x) + L_{\Delta f} h_1(x) + \left[l_{g1} h_1(x) + \qquad \left[L_{g2} h_1(x) + L\Delta_{g2} h_1(x)\right]\right] u_2$$
$$\hat{Z}_2 = L_f h_2(x) + L_{\Delta f} 2(x) + \left[l_{g1} h_2(x) + \left[L_{g2} h_2(x) + \qquad L\Delta_{g2} h_1(x)\right]\right] u_2 \qquad (13)$$

The partial feedback linearization scheme for the PV system can be written as,

$$\hat{Z}_1 = 1.38\omega I_d - 1.044\frac{R}{L}I_q = 1.25\frac{E_q}{L} + \qquad 1.20\frac{V_{PV}}{L}K_q$$
$$\hat{Z}_2 = \frac{1.16}{C}I_{PV} - \frac{1.10}{C}I_d K_d - \frac{1.15}{C}I_q K_q \qquad (14)$$

If V_1 and V_2 is the linear control input to the non-linear controller, then the equation (14) becomes,

$$V_1 = 1.38\omega I_d - 1.044\frac{R}{L}I_q = 1.25\frac{E_q}{L} + \qquad 1.20\frac{V_{PV}}{L}K_q$$
$$V_2 = \frac{1.16}{C}I_{PV} - \frac{1.10}{C}I_d K_d - \frac{1.15}{C}I_q K_q \qquad (15)$$

The above equation (15) can be obtained by using linear control technique. In this paper two PI linear controller are used. Then the non-linear controller output control law equation is,

$$K_d = 0.86\frac{L}{V_{PV}}\left(V_1 + 1.38\omega I_d + 1.044\frac{R}{L}I_q + \qquad 1.24\frac{E_q}{L}\right)$$

$$K_q = -0.89\frac{C}{I_q}\left(V_2 + 1.18\frac{I_{PV}}{C} - 1.10\frac{I_d}{C}K_d\right) \qquad (16)$$

4.1. Implementation Block Diagram of the System

The partial feedback linearizing controllers are sensitive to the system parameters, it is essential to have an exact system model in order to achieve good performance. However, for real life grid-connected PV systems, there often exist inevitable uncertainties within uncertainties within the constructed models. In addition, there exist uncertain parameters that are not exactly known or are difficult to estimate. Therefore, to evaluate the performance of the designed non-linear control scheme, it is essential to consider these uncertainties

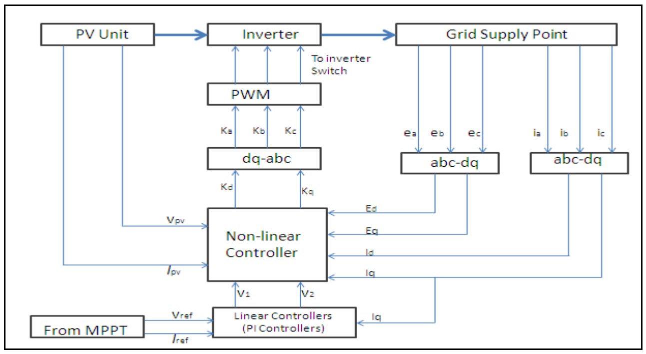

Figure 4: Implementation block diagram of the system

The implementation block diagram of the scheme is shown Figure 4, in which the modeled uncertainties have been included with the nominal PV system model. From Figure.4 it can also be seen that the three-phase grid voltages and currents are transformed into direct and quadrature axis components through abc– dq0transformation the designed scheme is the combination of linear PI controller equation (15) and the partial feedback linearizing scheme equation (16). Finally, the control inputs are again transformed into three-phase components using dq0 – abc transformation to implement them through the inverter switches. To make the input signals suitable for switches, the PWM technique is used.

5. Simulation Model and Results

The basic PV system is modeled based on the equations in equivalent circuit of the PV cell. In this paper, totally ten panel are made. Each single panel are in the ratings of 4,7A 25.04V 117.07W. It is done by using MATLAB Simulink.

Perturbation & Observation (P&O) MPPT technique are used in this project to extract the maximum power from PV unit under climatic changing condition In MPPT technique the present value and previous value can be compared and depend upon the value, MPPT technique can increase or decrease the voltage and power.

Boost converter are used to boost up the PV output voltage to synchronize the inverter to the grid by using the MPPT technique, the boost converter output voltage can be made constant under climatic changing condition

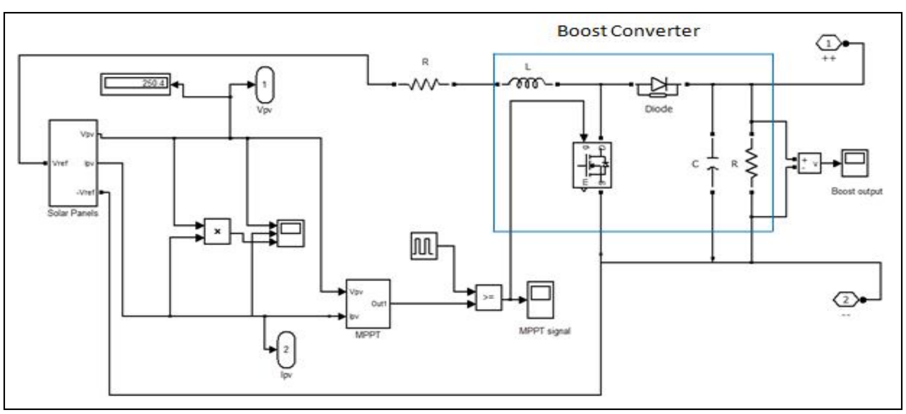

Figure 5: simulation subsystems of the PV unit and MPPT and the boost converter

The Figure 5 shows the simulation subsystem of the PV unit and MPPT and the boost converter.

The overall simulation diagram of the system is shown in the Figure 6

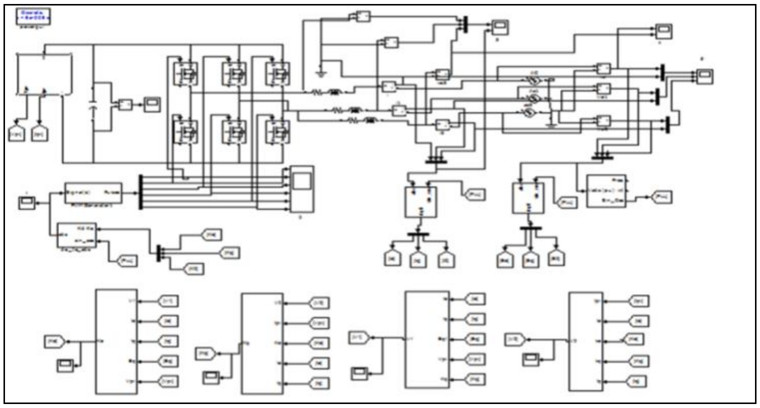

Figure 6: Overall simulation diagram of the proposed system

5.1. Normal Climatic Condition

The output of the PV unit under normal irradiation condition is shown in Figure 7.In this condition the irradiation is considered as 100 W/$m2$

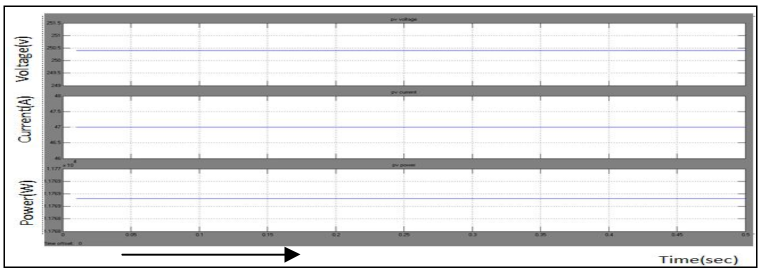

Figure 7: Output waveform of the PV unit under normal condition

The output of the PV unit is 250.4V then it can be boost up to 600V and then the voltage is given to the normal three phase voltage source inverter through DC-link capacitor The DC-link voltage can be controlled by using the MPPT technique.

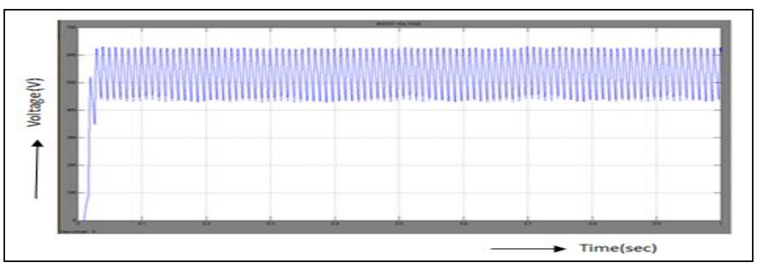

Figure 8: Output waveform of the DC-link capacitor

The controller has been modeled based on the model equation of the proposed system and the output of the controller after converting the dqo to abc is shown in the Figure 9. The controllers input are taken from the PV unit voltage and current and the grid voltage and current after converting the abc to dq0 through PLL.

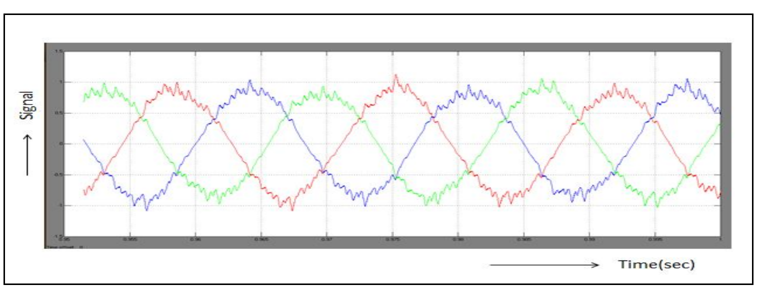

Figure 9: output waveform of the controller

The main objective of the proposed system is the output voltage of an inverter must be in synchronous with the grid voltage then only the PV system can be interface to the grid From the Figure 10 shows that the proposed system is synchronized

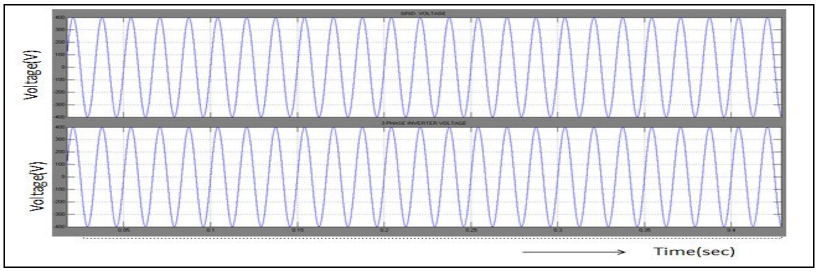

Figure 10: Output voltages of the inverter and grid

The grid current and the voltage must be in phase to attain unity power factor is the objective of the proposed system is shown in Figure 11

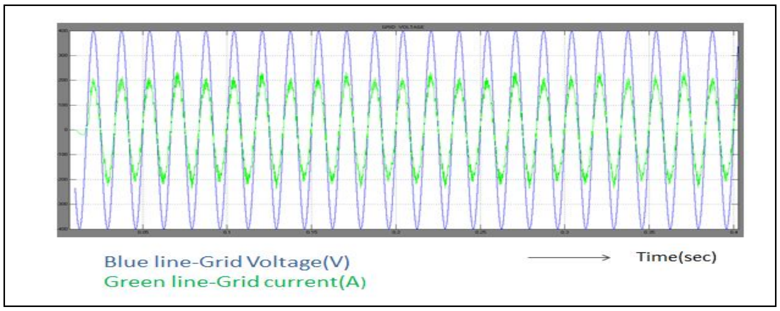

Figure 11: Output of the grid voltage and current

5.2. Climatic Changing Condition

The PV system is not a linear system so that PV system depend upon the solar irradiation then the Figure 12 shows the output waveform of the PV unit under changing condition of irradiation decreases to 70% of the normal value which is equal to 70 W/m2

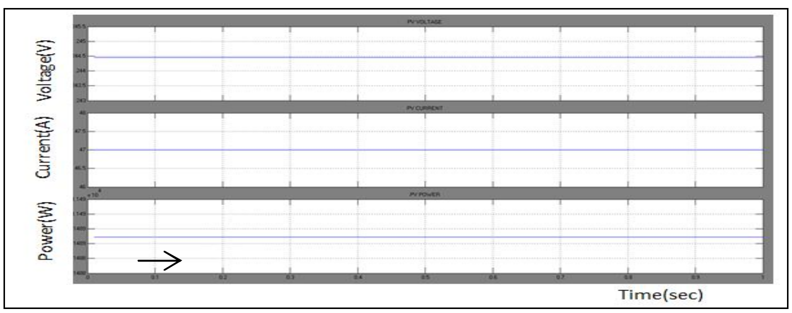

Figure 12: Output waveform of the PV unit under climatic changing condition

The output voltage and current of grid is in phase under climatic changing condition is shown in Figure 13. The controller can perform well under changing condition.

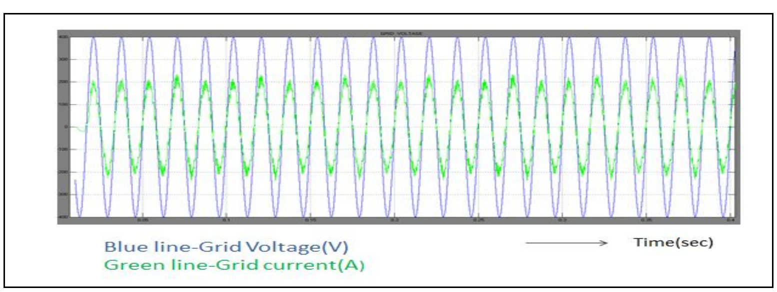

Figure 13: Output voltage and current of the grid under changing condition

The output voltage of the three phase grid is shown in the Figure14,

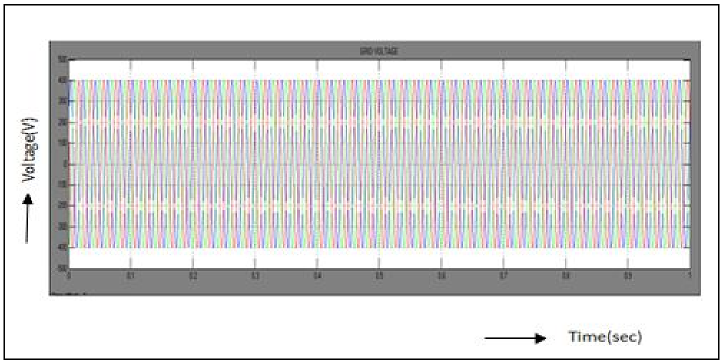

Figure 14: Output voltage of the three phase grid

N_s	*36*
N_p	*10*
DC-link capacitance	$1e^{-6}$
Filter Resistance	*1*
Filter Inductance	$1e^{-3}$

Table 1: Appendix

6. Conclusion

In this project, stability enhancement of a three-phase grid-connected PV system is done by modeling the uncertainties to ensure the operation of the system at unity power factor., The partial feedback linearization approach is used, and with the designed scheme, only the upper bounds of the PV systems parameters and states need to be known rather than network parameters, system operating points. The resulting scheme enhances the overall stability of a three-phase grid connected PV system, considering admissible network uncertainties. Thus, this stabilization scheme has good stabilization against the PV system parameter variations, irrespective of the network parameters and configuration

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