International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 03, March-2015

Modeling and Analysis of Robust Nonlinear Controller for Three Phase Grid Connected System Under Structured Uncertainties

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Abstract **- Among the various non conventional energy sources PV is a promising alternative source, because it has many merits. The power generated is depends on the irradiation from the sun and weather conditions. Since the power from sun is not constant during a day, it varies with time. MPP trackers are used to get the maximum power from sun. In the proposed method Incremental Conductance (INCC) method is used. The linear controllers do not account for uncertainties in the grid connected PV system. To overcome the limitations of linear controllers a robust nonlinear controller is proposed in this paper. By using the proposed controller we can maintain the grid voltage and currents are in phase with each other .The performance of the proposed Robust Partial Feed Back Linearizing Controller (RPFBLC) is compared with the Partial Feed Back Linearizing Controller (PFBLC). By using simulation results we conclude that with the proposed method we can maintain the system voltage and current are in phase with each other .we can maintain system in stable and also maintain the power factor at unity.**

Index terms: Grid connected system, PV energy, PI controller, Uncertainties.

I.INTRODUCTION

Now a day the population was increasing day by day, at the same way the industries are also increasing. So the demand for power is also increasing. As the conventional sources of energy are depleting and the cost of energy was rising day by day. In order to minimize the cost and to generate the power the alternative sources of energy are non conventional energy sources. Among the various sources of non conventional energy sources, PV is a promising source. Since it exhibits many merits such as cleanness, little maintenance and less cost etc. Since the power from sun is depends on the irradiation and weather conditions. So MPPT plays an important role in the PV system [1]-[5]. They are used to track the maximum power from sun. In a grid connected PV System the control objectives are met by using PWM technique. It consists of two cascaded control loops [6]. The inner current control loop is used to maintain the power quality, to control the duty ratio for the generation of sinusoidal output current and the outer control loop is voltage control loop which is used to track the MPP. Normally current controllers are used in tracking method. The two typical configurations of a grid connected PV system are single stage grid connected and multi stage grid connected system [7]. Though multistage systems are reported for certain applications, grid connected PV systems usually employ two stages to appropriately deliver the power in to the grid. In the first stage DC/DC converter is used for boosting and to track MPP, the second stage is used to convert the PV voltage to ac voltage using an IGBT inverter [8]. The LCL filter provides advantages in costs and dynamics since smaller inductors can be used [9]. The uncertainties that are present in the PV system are system conditions, weather conditions.

II.MODELING AND SYSTEM DESCRIPTION

A PV cell is same as like simple p-n junction diode. It is a semi conductor diode. It is constructed in such a way that light can penetrate into the region of the p-n junction. According to the principle "when the sun light falls on the PV panels, the PV panel can generate excess of holes and electrons". The holes are moved to n-type and electrons are moved to p-type of the semiconductor then the breakdown of the junction occurs. This can cause to flow the charge through an external circuit to produce power as shown in below fig (1).

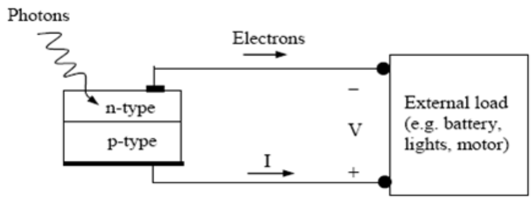


Fig.1 External Circuit to Produce Power

The above circuit can be replaced by an equivalent circuit. The simplest equivalent circuit of a solar cell is a current source in parallel with a diode as shown in below fig (2).

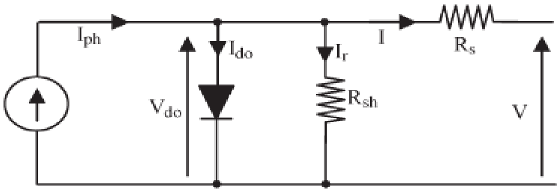


Fig.2 Equivalent circuit of solar cell

From the above fig, when the power supply is ON the current I_{ph} is produced, which depends on irradiation. The produced I_{ph} is divided in to two quantities as I_d and I. Where I is the current given to load and Id is diode current. The output Current I and the output voltage V of a solar cell are given by

$$I = I_{ph} - I_{d0} - \frac{v_{d0}}{R_{sh}}$$

$$= I_{ph} - I_0 \left(\exp\left(\frac{q.v_{d0}}{n.k.T}\right) - 1\right) - \frac{v_{d0}}{R_{sh}} \quad (1)$$

And

$$V = v_{d0} - R_s I \quad (2)$$

Here, I_{ph} is the photocurrent, I_0 is the reverse saturation current, I_{d0} is the average current through the diode, n is the diode factor, q is the electron charge (q = 1.6*10^{-19}), k is the Boltzmann's constant (k = 1.38*10^{-23}), and T is the solar array panel temperature. R_s is the series resistance of the solar cell; this value is normally very small. R_{sh} is the equivalent shunt resistance of the solar array, and its value is very large. In general, the output current of a solar cell is expressed by

$$I = I_{ph} - I_0 \left(\exp\left(\frac{q}{n.k.T}(V + R_s I)\right) - 1\right) - \left(\frac{V + RsI}{Rsh}\right) \quad (3)$$

In the above equation the resistances are neglected, thus the above equation can be simplified to

$$I = I_{ph} - I_0 \left(\exp\left(\frac{q}{n.k.T} V\right) - 1\right) \quad (4)$$

If the circuit is opened,the output current I=0,then V_{0c} is expressed as

$$V_{0c} = \left(\frac{n.k.T}{q}\right) \ln\left(\frac{Iph}{Io} + 1\right) \approx \left(\frac{n.k.T}{q}\right) \ln\left(\frac{Iph}{Io}\right) \quad (5)$$

Similarly ,when short circuited V=0,then

$$I_{sc} = I = \left(\frac{I_{ph}}{1 + \frac{R_s}{R_{sh}}}\right)$$

And power become as

$$P = VI = \left(I_{ph} - I_{d0} - \frac{v_{d0}}{R_{sh}}\right) V$$

III.MODELING OF THRRE PHASE GRID CONNECTED SYSTEM

The below figure (5) shows the schematic diagram of the three phase grid connected system. The two typical configurations of a grid connected system are single stage and multi stages [10]. In single stage system we can use only inverter to convert the generated DC power in to ac high power.

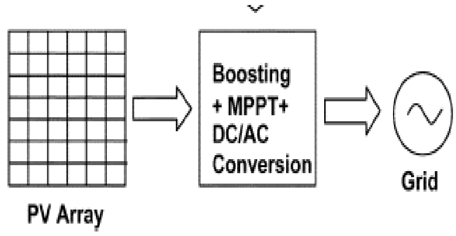


Fig.3 single stage grid connected system

Though the multi stages are available, mostly we are using two stage systems. In two stages the first stage is used to boost the PV array Voltage and to track the maximum power and the second stage is used for the conversion of this power in to high quality ac voltage. In recent years, the grid connected PV systems have become more popular because they do not need battery backups to ensure MPPT.

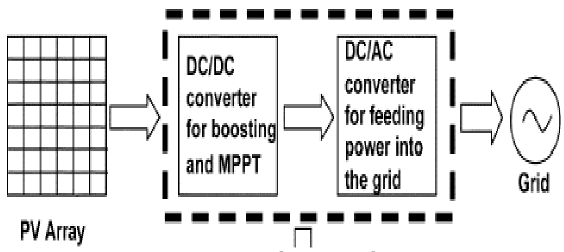


Fig.4 Two stage grid connected system

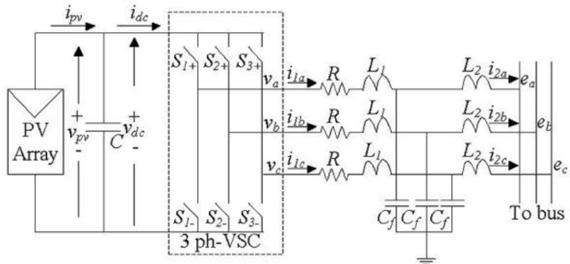


Fig.5 Three phase grid connected system

Now, by applying KCL at the node where DC link is connected, we get

$$\dot{v_{pv}} = \frac{1}{C}(i_{pv} - i_{dc}) \quad (6)$$

Similarly applying Kirchhoff's Voltage Law (KVL) at the inverter side loop, we get

$$\dot{i_{1a}} = \frac{-R}{L_1} i_{1a} - \frac{v_{cfa}}{L_1} + \frac{v_{pv}}{3L_1}(2K_a - K_b - K_c) \quad (7)$$

$$\dot{i_{1b}} = \frac{-R}{L_1} i_{1b} - \frac{v_{cfb}}{L_1} + \frac{v_{pv}}{3L_1}(K_a + 2K_b - K_c) \quad (8)$$

$$\dot{i_{1c}} = \frac{-R}{L1} i_{1c} - \frac{v_{cfc}}{L_1} + \frac{v_{pv}}{3L_1}(K_a - K_b + 2K_c) \qquad (9)$$

Where K_a, K_b, and K_c are the input switching signals. And i_{1a}, i_{1b}, i_{1c} are the output currents of the inverter. But the input current of the inverter i_{dc} can be written as

$$i_{dc} = i_{1a}K_a + i_{1b}K_b + i_{1c}K_c \qquad (10)$$

So (6) becomes as

$$\dot{v_{pv}} = \frac{1}{C}(i_{pv} - i_{1a}K_a + i_{1b}K_b + i_{1c}K_c) \qquad (11)$$

Similarly applying KCL at C_f node

$$\dot{v_{cfa}} = \frac{1}{C_f}(i_{1a} - i_{2a})$$

$$\dot{v_{cfb}} = \frac{1}{C_f}(i_{1b} - i_{2b}) \qquad (12)$$

$$\dot{v_{cfc}} = \frac{1}{C_f}(i_{1c} - i_{2c})$$

Applying KVL at the LCL filter (output side)

$$\dot{i_{2a}} = \frac{1}{L2}(v_{cfa} - e_a)$$

$$\dot{i_{2b}} = \frac{1}{L2}(v_{cfb} - e_b) \qquad (13)$$

$$\dot{i_{2c}} = \frac{1}{L2}(v_{cfc} - e_c)$$

Where i_{2a}, i_{2b}, i_{2c} are the output currents from the inverter. The complete model of a three-phase grid-connected PV can be presented by above equation which are nonlinear and time variant. This time variant model can be converted into time invariant model by applying dq transformation using the angular frequency (ώ) of the grid, rotating reference frame synchronized with grid where the d component of the grid voltage Ed is zero. By using dq transformation, above equations can be written as

$$\dot{I_{1d}} = \frac{-R}{L1} I_{1d} + \omega I_{1q} - \frac{v_{cfd}}{L1} + \frac{v_{pv}}{L1} K_d$$

$$\dot{I_{1q}} = \frac{-R}{L1} I_{1q} + \omega I_{1d} - \frac{v_{cfq}}{L1} + \frac{v_{pv}}{L1} K_q$$

$$\dot{v_{pv}} = \frac{1}{C} i_{pv} - \frac{1}{C} I_{1d}K_d - \frac{1}{C} I_{1q}K_q \qquad (14)$$

$$\dot{v_{cfd}} = \frac{1}{C_f}(i_{1d} - i_{2d}) + \omega v_{cfq}$$

$$\dot{v_{cfq}} = \frac{1}{C_f}(i_{1q} - i_{2q}) - \omega v_{cfd}$$

$$\dot{i_{2d}} = \frac{1}{L2}(v_{cfd} - E_d) + \omega I_{2q}$$

$$\dot{i_{2q}} = \frac{1}{L2}(v_{cfq} - E_q) - \omega I_{2d}$$

The above (14) represents the three phase grid connected lossless PV system, with an LCL filter. Where K_d, K_q are the switching signals in the dq frame and the transformation matrix (T_{abc}^{dq}) can be written as

$$T_{abc}^{dq} = \frac{2}{3}\begin{pmatrix} cos\omega t & \cos(\omega t - 120) & \cos(\omega t + 120) \\ sin\omega t & \sin(\omega t - 120) & \sin(\omega t + 120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

IV. UNCERTAINITY MODELING

Since the output power of the PV system is not constant during a day. It varies with the time. The output power depends on the intensity of the solar irradiation which is uncertain because of the changes in weather conditions. These changes are modeled as uncertainties in current out (i_{pv}) of the solar panels which, in turn, causes uncertainties in the current (in the dq -frame, i_{1d}, i_{1q}, i_{2d} and i_{2q}) injected into the grid. Thus the three-phase grid-connected PV system can be represented by the following equation (16) in the presence of uncertainties.

$$\dot{X} = f(x) + g_1(x)\, u_1 + g_2(x)\, u_2$$
$$y_1 = h_1(x) \qquad (15)$$
$$y_2 = h_2(x)$$

The above equation (15) represents the mathematical model of the partial feedback Linearizing controller having the two control inputs K_d and K_q.

$$\dot{X} = [f(x) + \Delta f(x)] + [g_1(x) + \Delta g_1(x)]u_1 + [g_2(x) + \Delta g_2(x)]u_2$$

$$y_1 = h_1(x) \qquad (16)$$
$$y_2 = h_2(x)$$

Where

$$\Delta f(x) = \begin{pmatrix} \Delta f_1(x) \\ \Delta f_2(x) \\ \Delta f_3(x) \\ \Delta f_4(x) \\ \Delta f_5(x) \\ \Delta f_6(x) \\ \Delta f_7(x) \end{pmatrix} \qquad (17)$$

And

$$\Delta g(x) = \begin{pmatrix} \Delta g_{11}(x) & 0 \\ 0 & \Delta g_{22}(x) \\ \Delta g_{31}(x) & \Delta g_{32}(x) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \qquad (18)$$

Where $\Delta f(x)$ and $\Delta g(x)$ are the uncertainties. And finally $\Delta f(x)$, $\Delta g(x)$ for the PV system under study can be obtained as

$$\Delta f(x)=\begin{bmatrix} -0.025\frac{R}{L_1}I_{1d} + 0.6\omega I_{1q} - 0.23\frac{v_{cfd}}{L_1} \\ -0.36\omega I_{1d} - 0.042\frac{R}{L_1}I_{1q} - 0.23\frac{v_{cfq}}{L_1} \\ 0.16\frac{1}{C}i_{pv} \\ 0.2\omega v_{cfq} + 0.72\frac{1}{C_f}(I_{1d} - I_{2d}) \\ -0.12\omega v_{cfd} + 1.2\frac{1}{C_f}(I_{1q} - I_{2q}) \\ 0.6\omega I_{2q} + 2\frac{2}{L_2}(0.12v_{cfd} - E_d) \\ -0.36\omega I_{2d} + \frac{2}{L_2}(0.2v_{cfq} - E_q) \end{bmatrix} \quad (19)$$

And

$$\Delta g(x) = \begin{bmatrix} 0.18\frac{v_{pv}}{L_1} & 0 \\ 0 & 0.18\frac{v_{pv}}{L_1} \\ -0.08\frac{I_{1d}}{C} & -0.14\frac{I_{1q}}{C} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (20)$$

The proposed robust partial feedback Linearizing controller design by considering is as shown in the below section.

V.PROPOSED CONTROLLER DESIGN

To design a proposed robust controller the following steps are followed

Step 1: Consider a nonlinear coordinate function

$$\widetilde{z_1} = \widetilde{\emptyset_1}(x)$$
$$\widetilde{z_2} = \widetilde{\emptyset_2}(x)$$

Where $\emptyset_1$, $\emptyset_2$ are the functions of x.

For Three phase grid connected system, we consider

$$\widetilde{z_1} = \widetilde{\emptyset_1}(x) = h_1(x) = I_q$$

And

$$\widetilde{z_2} = \widetilde{\emptyset_2}(x) = h_2(x) = v_{pv}$$

Step 2: From the above equation obtain the robust partially linearized system for uncertainties.

$$\dot{\widetilde{z_1}} = \frac{\delta f_1(x)}{\delta x} = L_f h_1(x) + L_{\Delta f} h_1(x) + [L_{g1}h_1(x) + L_{\Delta g_1}h_1(x)]u_1 + [L_{g2}h_1(x) + L_{\Delta g_2}h_1(x)]u_2 \quad (21)$$

$$\dot{\widetilde{z_1}} = \frac{\delta f_2(x)}{\delta x} = L_f h_2(x) + L_{\Delta f} h_2(x) + [L_{g1}h_2(x) + L_{\Delta g_1}h_2(x)]u_1 + [L_{g2}h_2(x) + L_{\Delta g_2}h_2(x)]u_2$$

Step 3: Derive the state equations for PV systems.

$$\dot{\widetilde{z_1}} = -1.36\omega I_{1d} - 1.042\frac{R}{L_1}I_q - 1.23\frac{v_{cfq}}{L_1} + 1.18\frac{v_{pv}}{L_1} \quad (22)$$

$$\dot{\widetilde{z_2}} = \frac{1.16}{C}i_{pv} - \frac{1.08}{C}I_{1d}K_d - \frac{1.14}{C}I_{1q}K_q$$

If we consider $\widetilde{v_1}$ and $\widetilde{v_2}$ as linear control inputs, then above equation becomes

$$\dot{\widetilde{z_1}} = \widetilde{v_1}$$
$$\dot{\widetilde{z_2}} = \widetilde{v_2} \quad (23)$$

Where

$$\widetilde{v_1} = -1.36\omega I_{1d} - 1.042\frac{R}{L_1}I_q - 1.23\frac{v_{cfq}}{L_1} + 1.18\frac{v_{pv}}{L_1} \quad (24)$$

$$\widetilde{v_2} = \frac{1.16}{C}i_{pv} - \frac{1.08}{C}I_{1d}K_d - \frac{1.14}{C}I_{1q}K_q$$

From the above equation we calculate physical control inputs K_d and K_q.

Step 4: Find out the feedback linearized system.

It needs control law as

$$\lim_{t\to\infty} h_i(x) \to 0 \quad (25)$$

I states that as time tends to infinity the linear system decays to zero.

$$[\widetilde{z_1}\ \widetilde{z_2}\ \cdots\cdots\ \widetilde{z_r}]^T \to 0 \quad (26)$$

For the proposed system

$$\widetilde{z_1} = 0$$
$$\widetilde{z_2} = 0 \quad (27)$$

Let us consider

$$\hat{z} = \widehat{\emptyset}(x)$$

This is in nonlinear state.

To ensure the stability of the system $\hat{z}$ is selected in such a way that it satisfies the following condition.

$$L_{g_1}\widehat{\emptyset}(x) = 0$$
$$L_{g_2}\widehat{\emptyset}(x) = 0$$

For the PV system the above equation is satisfied if we consider

$$\hat{z} = \widehat{\emptyset}(x) = \begin{bmatrix} \widehat{z_3} \\ \widehat{z_4} \\ \widehat{z_5} \\ \widehat{z_6} \\ \widehat{z_7} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}LI_{1d}^2 + \frac{1}{2}LI_{1q}^2 + \frac{1}{2}Cv_{pv}^2 \\ v_{cfd} \\ v_{cfd} \\ I_{2d} \\ I_{2q} \end{bmatrix} \quad (28)$$

Thus the dynamics of $\hat{z} = \widehat{\emptyset}(x)$ can be expressed as

$$\dot{\hat{z}} = L_f \widehat{\emptyset}(x) \quad (29)$$

For $\dot{\hat{z}}_3$,the dynamics can be simplified as(25)

$$\dot{\hat{z}}_3 = -\frac{2R}{L}\hat{z}_3 \quad (30)$$

The above equation represents a stable system.Similarly the dynamics of the remaining states can be calculated by using (30) as

$\dot{\hat{z}}_1 = 0$; with i=4, 5, 6 and 7.

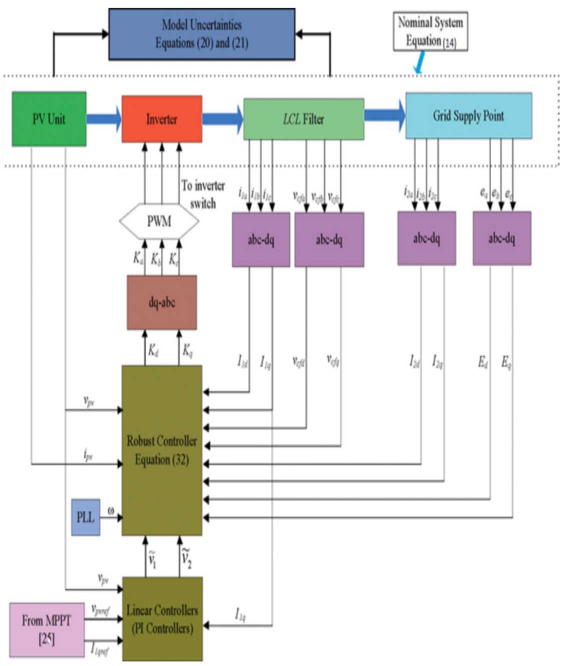
Step 5: Derivation of the robust control law.
The control law is obtained from (25) as follows.

$$K_d = \frac{0.85L}{v_{pv}}\left(\widetilde{v_1} + 1.36\omega I_{1d} + \frac{1.042\ R}{L_1} I_{1q} + \frac{1.23}{L_1} v_{cfq}\right) \quad (31)$$

$$K_q = -0.88\frac{C}{I_q}\left(\widetilde{v_2} + 1.16\frac{i_{pv}}{C} - 1.08\frac{I_{1d}}{C} K_d\right)$$

The above equation (31) represents the final robust control law, which is having uncertainties.

VI.TESTING OF THE PROPOSED CONTROLLER



Case 1: *Controller performance under standard atmospheric conditions*:

In this the standard values of solar irradiation ($1KW^{-2}$) and environmental temperature (298K) are considered. Under these conditions the grid voltage and currents are in phase with each other. From the below fig (7) the PFBLC is unable to transmit the total 50KW power to the load, when there is variation in of 25% in irradiance and 70% of uncertainties in the PV system(green line). But the RPFBLC maintain the voltages and currents in phase with each other (red line) and maintain the power factor at unity.

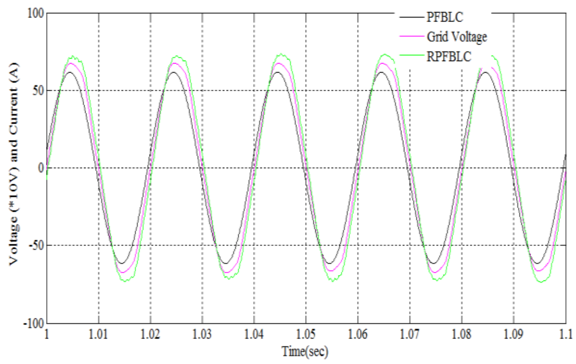


Fig.7.controllerperformanceatstandard atmospheric conditions

Case 2: *Under changes in atmospheric conditions*:

Here consider that PV unit operates normally until t=1.1s, after that consider that there is reduction in irradiation below 70%. At this time PFBLC is not able to maintain the voltage and currents in phase, but it is able to maintain the stability of the system. Whereas by using RPFBLC there are no phase differences. From 1.1s to 1.2 consider that there are changes in atmospheric conditions as shown in below.

The effectiveness of the proposed controller is tested for different system conditions and changes in atmospheric conditions and the results are compared with the controller doesn't have robustness.

Consider a three phase grid connected system, which is having an PV array with 20 strings and each string is subdivided into 20 modules having a rating of voltage as 43.5V.The current of each string here used is 2.8375A.So the total output voltage from the PV array is 870V, total output current is 57.47A.So, The total output power from the PV array is 50KW.During uncertainties also we have to transmit this total output power to the grid [11]. In the proposed controller, the value of the dc link capacitor is $400\mu F$,the line resistance is 0.1Ω,inductance is 10mH.The grid voltage is 660V ,frequency is 50HZ and consider the switching frequency of the inverter as 10KHZ.In this an PI controller [13]is used to minimize the error signal. It automatically tuned for the error and gives the pure voltage signals.LCL filter is used to reduce the harmonics. The value of the capacitor and inductor used in simulation process are $3.1\mu F$ and 10mH respectively. The grid and LCL filter outputs are having three phases are converted in to two phases by using abc-dq transformation and given to the robust controller. The output from the controller is finally given to the inverter with the help of PWM converter as shown below.

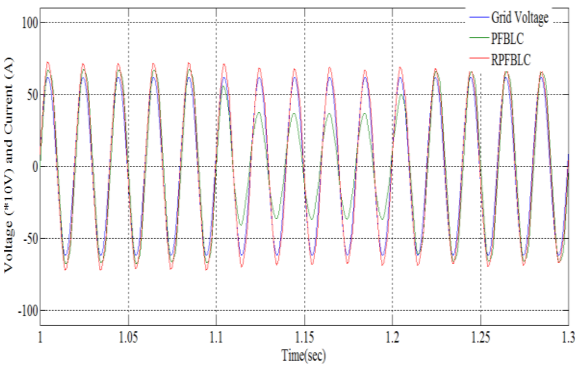


Fig.8performance at changing atmospheric conditions

Case 3: *Controller performance during short circuit faults:*

In this study consider that

- Fault occurs at t=1.5s
- Fault cleared at t=1.6s

The robust controller performance is tested by considering standard atmospheric conditions .In this section it is analyzed in pre fault and post fault conditions.

A).*Controller performance during single line to ground fault*:

When a single line to ground fault occur at the inverter, then there is a voltage imbalance due to the negative sequence voltage component. Since the grid voltage is stiff, this imbalance may also occur at grid supply point.

Consider that there is a single line to ground fault occurred at phase ’B’ to the ground. The voltage of phase ‘B’ only reduced to zero as shown below.

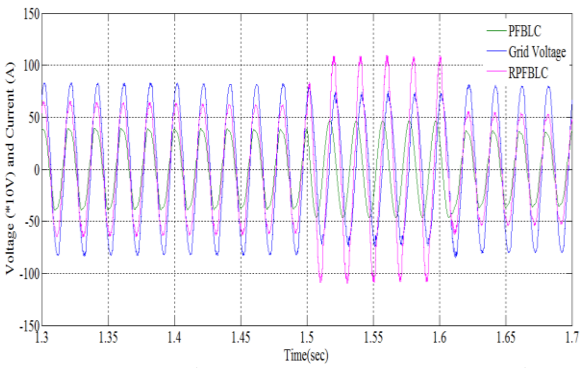


Fig.9.Controller performance during single line to ground fault

Compare to three phase short circuit fault there is less phase difference between voltage and current. The positive sequence currents and negative sequence powers of single line to ground fault are as shown in below figures 10 and 11 respectively.

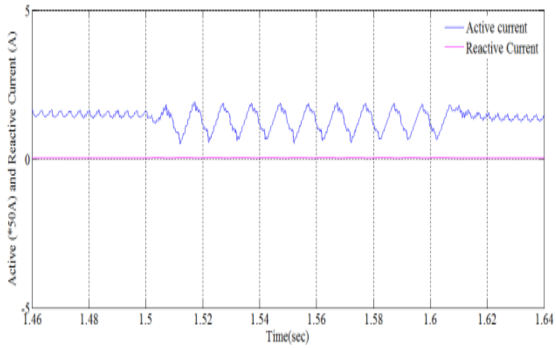


Fig.10.Positive sequence active (I_q) and reactive (I_d) currents during single line to ground faults

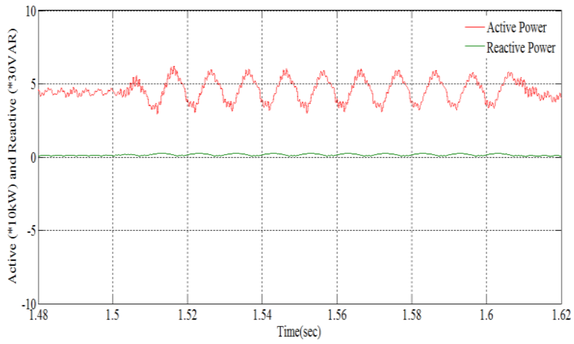


Fig.11.Negative sequence active (P) and reactive (Q) powers during single line to ground fault.

B) *Controller performance during three phase short circuit fault:*

When these faults occur the three phase voltages are reduced to zero but the currents get increased rapidly. With the robust controller the post fault voltages and currents are in phase with each other. But there is still there is phase difference between voltage and current (green line) fig.10.

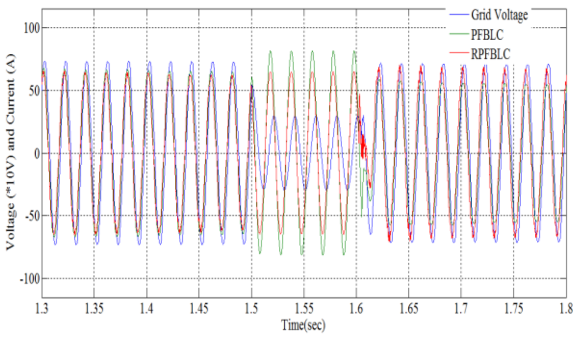


Fig.10.Controller performance during three phase short circuit fault

VII. CONCLUSION

A robust partial feedback Linearizing controller is the good controller for the grid connected PV system to maintain the grid voltage and currents in phase with each other and also maintain the power factor at unity. Instead of considering network parameters only PV system parameters and states need to be known. The resulting robust controller enhances the overall stability of the system under structured uncertainties. Future work will include the implementation of the proposed control scheme on a practical system.

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