PERFORMANCE ANALYSIS OF SINGLE PHASE BOOSTING INVERTER FOR GRID CONNECTED PV SYSTEM

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ABSTRACT

This paper presents a new nonlinear current control scheme for a single-phase grid-connected photovoltaic (PV) system. Partial feedback linearization is used for designing the controller, which linearizes the system partially and enables the controller design scheme for reduced-order PV systems. The proposed current control approach introduces the internal dynamics and the stability of the internal dynamics is a key requirement for the implementation of the controller. Based on the tracking of grid current to the reference current, the performance of the controller is evaluated by considering the changes in environmental conditions. A large system similar to a practical system is simulated under different operating conditions. In this paper a conventional hysteresis controller performance is compared with the non linear current controller. All the possible nonlinearities are very well canceled by the proposed controller designed approach by transforming the PV system into a reduced order linear system with stable internal dynamics.

Keywords: - *Current controller, grid-connected photovoltaic (PV) system, Lyapunov function, maximum power point tracking, partial feedback linearizing controller.*

1. INTRODUCTION

The energy sources are "the fossil fuels and nuclear fission" need for electric power. Burning oil, coal and natural gas pumps nitrogen oxide, sulphur dioxide and mercury and other toxic metals into our atmospheric, directly causing increasing incidents of lung disease, polluting soil and waters, damaging crops. Nuclear fission produces radioactive waste material that will remain deadly thousands of years. The apparent cost of oil, gas, coal and nuclear fission do not take into account the hidden health, environmental and economic cost to us all. Solar radiation provides a huge amount of energy to the earth. The total amount of energy, which is irradiated from the sun to the earth's surface, equals approximately 10,000 times the annual global energy consumption. Worldwide concerns of changing climate have made human beings to thought over the use of conventional & depleting energy sources. This in turn pushes us to sustainable energy sources like renewable energy. Some primary reasons for the power output fluctuation of PVS includes the movement of the clouds and there would be the time-difference in the fluctuation pattern among PVSs in a particular area. Therefore, the total output fluctuation of all PVSs would be relaxed due to the so-called "smoothing effect". Taking this into consideration, this study examines the fluctuation property of apparent electricity load on utility power plants, considering the PVSs power output into account as negative electricity load. The multi-points observed data on insolation is used to estimate the fluctuation property of PVSs power output [2],[3].

1.1 What is Photovoltaic?

A photovoltaic system is a power system designed to supply usable solar power by means of photovoltaics. Electricity can be produced from sun light through a process called photovoltaic (PV). "Photo" refers to light and "voltaic" to voltage. Because the source of light is usually the sun, they are called solar cells. A silicon PV cell is a consisting of a very thin layer of phosphorous doped (N- type) silicon on top of a thicker layer of boron-doped (P-type) silicon. An electricity field is created near the top surface of cell where these two materials are in contact (the

P-N junction). When sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to light- stimulated electrons, resulting in a flow of current when the cell is connected to an electrical load. Photovoltaic offer the ability to generate electricity in a clean, quiet and reliable way [1][17].

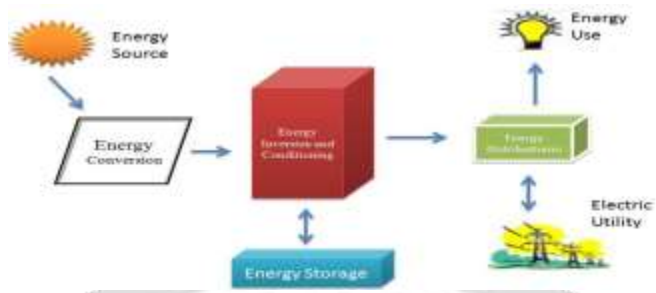


Fig 1. Major Photovoltaic System Component

1.2 Types of PV Systems

PV systems can be very simple, just a PV module and load, as in the direct powering of a water pump motor, or more complex, as in a system to power a house. While a water pump may only need to operate when the sun shines, the house system will need to operate day and night fig 2 below shows the basic Solar cell.

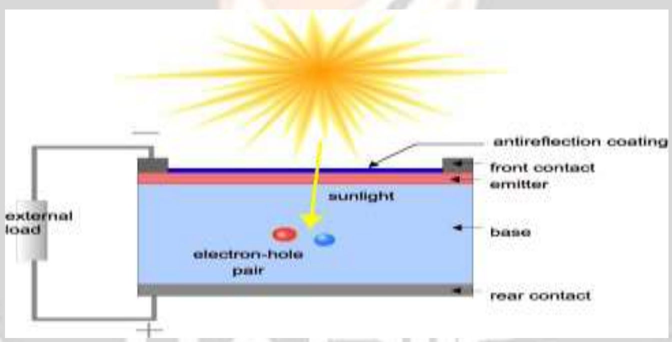


Fig 2 Basic Solar Cell

1.2.1. Stand-Alone Systems

Stand-alone systems rely on PV power only. These systems can comprise only PV modules and a load or can include batteries for energy storage.

1.2.2. Grid-Connected Systems

Grid-connected PV systems have become increasingly popular as building integrated application. These systems are connected to the grid through inverters, and do not require batteries because the grid can accept the electricity that a PV generator can supply.

1.2.3. Hybrid Systems

Hybrid systems consist of combination of PV modules and a complementary means of electricity generation such as a diesel, gas or wind generator. In order to optimize the operations of the two generators, hybrid systems typically require more sophisticated controls than stand-alone PV systems [18].

2. PROPOSED WORK

2.1 Block diagram PV system-

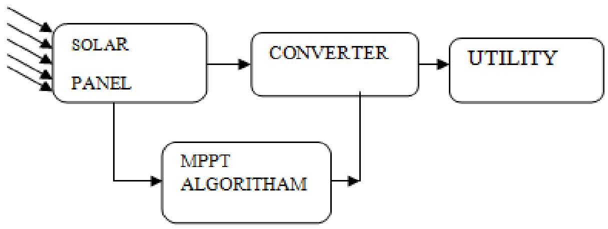


Fig 3- Block diagram PV system

The overall system consists of solar panel that generates power according to the irradiation levels. The MPPT algorithm calculates the duty cycle for the converter corresponding to the maximum power point. There will be one maximum power point for a particular irradiation. This makes the extraction of maximum power a complex task. The efficiency of the PV generation depends on maximum power extraction of PV system. Figure 3 above shows the PV system. Therefore, to maximize the efficiency of the renewable energy system, it is necessary to track the maximum power point of the PV array. The PV array has a single in service point that can supply maximum power to the load. This point is called the maximum power point (MPP) [16].

2.2 Proposed System Model-

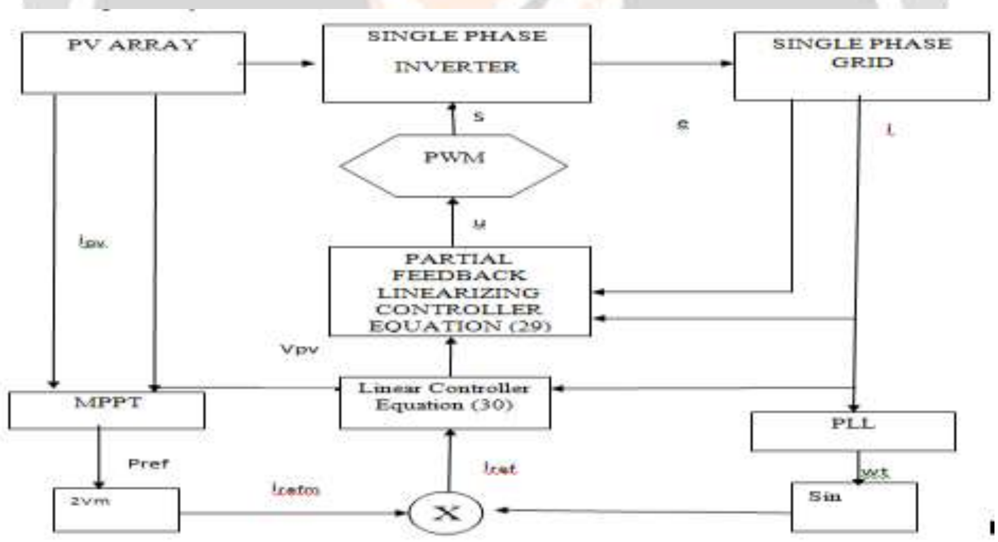


Fig 4 Proposed System Model

The proposed system as shown in fig 4 consists of a non-linear current controller for grid connected photovoltaic system as shown in figure 4. The main parts for it are the PV array, single phase inverter and single phase grid. The dc output of PV array is given to MPPT system. MPPT compares the generated PV output with reference input and sends the compared signal. The supply from single phase grid is taken upto the PLL and linear controller. The output of PLL and MPPT is compared and signal is given to the linear controller. At last the control signal for inverter bridge is given through Pulse Width Modulation (PWM). A conventional method of grid synchronization for grid connected DC/AC inverter is to duplicate the grid voltage so that output current reference has the same phase as the grid voltage .While this method is simple, it carries the distortions and transients from the grid to the output current, which is undesirable for grid connected applications. In addition, this method of grid synchronization cannot provide inverters the ability of controlling reactive power flow. Phase Locked Loops (PLL) circuits are used for frequency control. They can be configured as frequency multipliers, demodulators, tracking generators or clock recovery circuits. Each of these applications demands different characteristics but they all use the same basic circuit concept.

3. DESIGN OF THE SYSTEM

3.1. PV Cell and Array Modeling-

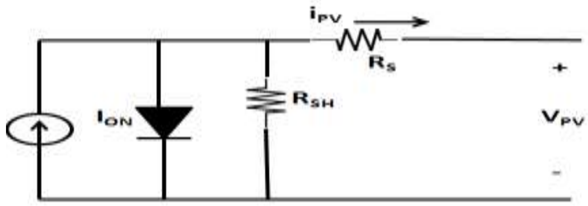


Fig 5 PV Cell and Array Modeling

A PV cell is a simple p–n junction diode which converts the irradiation into electricity. Fig 5 shows an equivalent circuit diagram of a PV cell which consists of a light generated current source I_L, a parallel diode, a shunt resistance Rsh, and a series resistance Rs. In Fig 5 I_{ON} is the diode current which can be written as,

$$I_{ON} = I_s[\exp[\alpha(V_{pv} + R_s i_{pv})] - 1] \quad (1)$$

where α is a constant which is equal to q/AkT_c where $k=1.3807*10^{-23}$ $JK^{-1}$is Boltzmann's constant, $q=1.6022 \times 10^{-19}$ is the charge of electron, Tc is cell's working temperature in Kelvin. A number of PV cells are put together and encapsulated with glass, plastic, and other transparent materials to protect from a harsh environment to form a PV module. To obtain the required voltage and power, a number of modules are connected in parallel to form a PV array. The array current i_{pv} can be written as,

$$i_{PV} = N_P I_L - N_P I_S[\exp[\alpha(\frac{v_{PV}}{N_S} + \frac{R_S i_{PV}}{N_P})] - 1] - \frac{N_P}{R_{sh}}(\frac{v_{pv}}{N_S} - \frac{R_S i_{PV}}{N_P}) \quad (2)$$

3.2. Single-Phase Grid-Connected PV System Modeling-

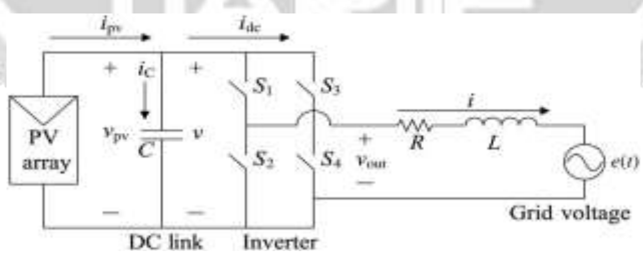


Fig 6 Single-Phase Grid-Connected PV System

In Fig 6 a single phase grid connected pv system is presented , where is the output of the dc link which is to be adjusted at a level through MPPT to make it suitable for the inverter, S_1,S_2,S_3 and S_4 and are the four switches of the inverter, R is the line resistance, L is the combination of filter and line inductance, i is the current injected into the grid, and $e(t)=V_m sinwt$ is the grid voltage where Vm is the maximum value of the grid voltage, $w= 2\Pi f$ is the angular frequency, and f is the grid frequency.

When S1 and S4 are ON, and S2 and S3, are OFF in Fig 5, applying Kirchhoff's voltage law (KVL) and KCL, the following relationship can be obtained:

$$\dot{V} = \frac{1}{c}(i_{pv} - i), i = \frac{1}{L}(V - Ri - e) \quad (3)$$

When S1 and S4 are OFF, and S2 and S3 are ON in Fig 6, again by applying KVL and KCL, the following relationship can be obtained, $\dot{V} = \frac{1}{c}(i_{pv} + i), i = \frac{1}{L}(V - Ri - e)$ (4)

Now by applying averaging technique, (3) and (4) can be written as,

$$\dot{V} = \frac{1}{c}(i_{pv} + iu(t)), i = \frac{1}{L}(vu(t) - Ri - e) \quad (5)$$

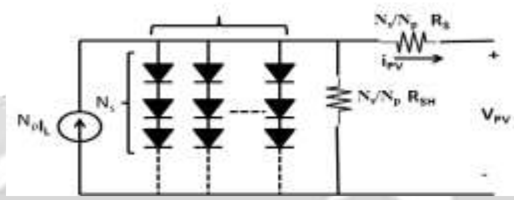


Fig 7 Equivalent Circuit Diagram of PV Array

Equation (5) represents the complete mathematical model of a single-phase grid connected PV system which is nonlinear due to the switching functions and diode current.

3.3 Partial Feedback Linearization and Partial Linearizability of PV System-

The mathematical model of a single-phase grid-connected PV system can be expressed as the general nonlinear system as follow: $\dot{x} = f(x) + g(x)u, y = h(x)$ (6)

Where $x = [v\ i]^T, f(x) = \begin{bmatrix} \frac{i_{pv}}{C} \\ \frac{-R_{i-c}}{L} \end{bmatrix}, \quad g(x) = \begin{bmatrix} \frac{-i}{C} \\ \frac{v}{L} \end{bmatrix}$ and $y=i$

The nonlinear system in (6) can be often linearized using feedback linearization.

Consider the following nonlinear coordinate transformation:

$$Z = [h\ L_f h(x) \dots \dots L_f^r h(x)]^T \quad (7)$$

Where r is an integer and $L_f h(x) = \partial h / \partial x f(x)$ is the Lie derivative of h(x) along f(x).[22] This transforms the nonlinear system (7) with the state vector x into a linear dynamic system with the state vector z provided that the following conditions are satisfied for: n=r hence, $L_g L_f^K h(x) = 0$ (8)

Where k < r-1 and $L_g L_F^k h(x) \neq 0$ (9)

Where Lg L_f^k h(x) is the Lie derivative of L_f h(x) along g(x). The integer r is known as the relative degree of the system corresponding to the output function h. If these conditions are satisfied, a linear controller can be designed for the linearized system which is also known as the exactly linearized system

$$\dot{z} = Az + Bv \quad (10)$$

Where A is the system matrix for the exactly linearized system, B is the input matrix for the exactly linearized system, and v is the new control input for the exactly linearized system. When r < n, we can perform only partial linearization and in this case, the transformed states z can be written as,

$$Z=\emptyset(x) = [\tilde{z} \ \ \hat{z}] \tag{11}$$

Where $\tilde{z}$ represents the states obtained from nonlinear coordinate transformation up to the order r and $\hat{z}$ represents the states related to the remaining n-r order. The dynamics of $\hat{z}$ are called the internal dynamics whose stability needs to be ensured before designing the linear controller for the following partially linearized system (11):

$$\dot{\tilde{z}} = \tilde{A}\tilde{z} + \tilde{B}\tilde{v} \tag{12}$$

Where $\tilde{A}$ the system matrix for the partially linearized system is, $\tilde{B}$ is the input matrix for the partially linearized system, $\tilde{v}$ and is the new control input for the partially linearized system. The partial Linearizability of the PV system represented in the form of (6) can be obtained by calculating the relative degree corresponding to the output function. The relative degree corresponding to h(x) = i can be calculated as

$$L_g h(x) = L_g L_F^{1-1} h(x) = \frac{V_{pv}}{L} \tag{13}$$

Which indicates r=1 and r < n as n = 2+. Therefore, the system is partially linearized for the chosen output function. To implement the feedback linearizing control for this system, the partial feedback linearization approach needs to be used provided that the internal dynamics of the system is stable.

3.4 Controller Design-

This section presents the controller design for a single-phase grid-connected PV system using the partial feedback linearization method as the system is partially linearized. Some steps need to be followed to obtain the control law through the proposed method which is discussed below:

Step 1: Nonlinear Coordinate Transformation and Partial Linearization:

A nonlinear coordinate transformation can be written as

$$\tilde{z} = \tilde{\emptyset}(x) \tag{14}$$

Where $\tilde{\emptyset}$ is the function of x . For a single-phase grid-connected PV system, we choose,

$$\widetilde{z1} = \widetilde{\emptyset_1}(x) = h(x) = i \tag{15}$$

Using the above transformation, the partially linearized system can be obtained as follows:

$$\dot{\widetilde{Z_1}} = \frac{\partial h(x)}{\partial x}\dot{x} = L_f h(x) + L_g h(x) u \tag{16}$$

For the PV system, $$\dot{\widetilde{Z1}} = \frac{-Ri-e}{L} + \frac{v}{L}u \tag{17}$$

Equation (18) can be written as the following linearized form:

$$\dot{\widetilde{Z1}} = \tilde{v} \tag{19}$$

3.5 MPPT Algorithm and Calculation of Reference Value-

The MPPT technique adjusts the PV array voltage in order to extract the available maximum power under all atmospheric conditions. The MPPT uses V_{pv} and i_{pv} to detect the slope and generates Pref to track the maximum power. In this paper, an incremental conductance method is used to obtain the maximum power. At maximum power point (MPP),

$$\frac{dp_{pv}}{dV_{pv}} = 0 \tag{20}$$

Where $P_{pv}=v_{pv}i_{pv}$ and if we this relation, then from (31)

$$\frac{\Delta i_{pv}}{\Delta v_{pv}} = -\frac{i_{pv}}{v_{pv}} \tag{21}$$

Here, $\frac{\Delta ipv}{\Delta vpv}$ is the incremental conductance and ipv/vpv is the instantaneous conductance. The MPP can be obtained by considering the following conditions:

1. at the MPP, $\frac{\Delta i_{pv}}{\Delta v_{pv}} = -\frac{i_{pv}}{v_{pv}}$

2. at the left of MPP, $\frac{\Delta i_{pv}}{\Delta v_{pv}} > -\frac{i_{pv}}{v_{pv}}$

3. At the of MPP, $\frac{\Delta i_{pv}}{\Delta v_{pv}} < -\frac{i_{pv}}{v_{pv}}$

If a PV system satisfies condition 1, the voltage is ascertained at the MPP voltage and fixed at this voltage until the MPPT encounters a change due to the changes in atmospheric conditions. If the atmospheric conditions change in such a way that the PV system holds condition 2, then it is essential to increase the reference voltage to achieve the MPPT and the opposite is true for condition 3.

At the MPP, the reference output power generated by the PV system is,

$$P_{ref} = v_{pv} i_{pv} \tag{22}$$

Since P_{ref} is also the maximum power which is supplied to the grid therefore, $P_{Grid} = ei = V_m \sin wt \times I_m \sin wt = \frac{v_m i_m}{2}(1-\cos 2wt)$ (23)

where I_m is the amplitude of the injected current. The average power (P_{av}) into the grid can be written as,

$$P_{av} = \frac{2}{T}\int_0^{\frac{T}{2}} \frac{v_m I_m}{2}(1-\cos 2wt)dt = \frac{v_m I_m}{2} \tag{24}$$

The MPPT technique controls P_{av} to follow the reference power Pref and at this stage the magnitude of the reference current I_{ref} will be I_{refm}. Therefore, the above equation can be written $P_{ref} = \frac{v_m I_{refm}}{2}$ (25)

Which implies that, $I_{refm} = \frac{2P_{ref}}{V_m}$ (26)

Finally, the reference current into the grid can be calculated as,

$$i_{ref} = \frac{2P_{ref}}{V_m}\sin wt \tag{27}$$

and this reference current is used for the PI controller where can be obtained using a phase lock loop (PLL).

3.6 MPPT Technique-

For a given temperature and irradiance, MPPT technique is to automatically ascertain the voltage VMPP or current IMPP to obtain the maximum power output *PMPP* and accordingly operates PV array. Under partial shading conditions it is possible to have multiple local maxima, but overall there is still only one true MPP. Most techniques respond to changes in both irradiance and temperature, but some are specifically more useful if temperature is approximately constant. Most techniques would automatically respond to changes in the array due to aging, though some are open-loop and would require periodic fine-tuning. In our context, the array will typically be connected to a power converter that can vary the current coming from the PV array.

3.6.1 Incremental Conductance (Inc-Cond) Technique-

For a PV system, the derivative of panel output power with its voltage is expressed as,

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} = I + V\frac{\Delta I}{\Delta V}, at MPP \frac{dP}{dV} = 0$$

The above equation is zero at MPP, positive on the left of the MPP and negative on the right of the MPP. So, it can also be given as,

i) $\frac{\Delta I}{\Delta V} = \frac{-I}{V}$ at MPP
ii) $\frac{\Delta I}{\Delta V} > \frac{-I}{V}$ at left of MPP
iii) $\frac{\Delta I}{\Delta V} < \frac{-I}{V}$ at right of MPP

Thus, MPP can be tracked by comparing the instantaneous conductance $\frac{I}{V}$ to the incremental conductance $\left(\frac{\Delta i}{\Delta v}\right)$. It is as efficient as P&O technique, good yields under rapidly changing atmospheric conditions. Here, also the same perturbation size problem as the P&O exists and an attempt has been made to solve by taking variable step size. But, it requires complex and expensive control circuits [6], [8].

4. SIMULATION MODELS

4.1 Performance Evaluation on a Simple System-

In this section, the performance of the designed controller is evaluated on the simple system as shown in Fig 8. To simulate the performance at this stage, a PV array consisting of ten PV cells, characterized by a rated current of 2.0 A, is connected in parallel. There are two bunch of PV cell, characterized by a rated voltage of 76.5 V, and connected in series. Thus, the total output voltage of the PV array is 153 V, the output current is 10 A, and the total power is 750 W. The value of the dc-link capacitor is 1000μF . The line resistance is 0.1 Ω and the inductance is 10 mH. The grid voltage is 240V and the frequency is 50 Hz. The performance of the designed controller is evaluated under standard and changing atmospheric conditions through the following case studies.

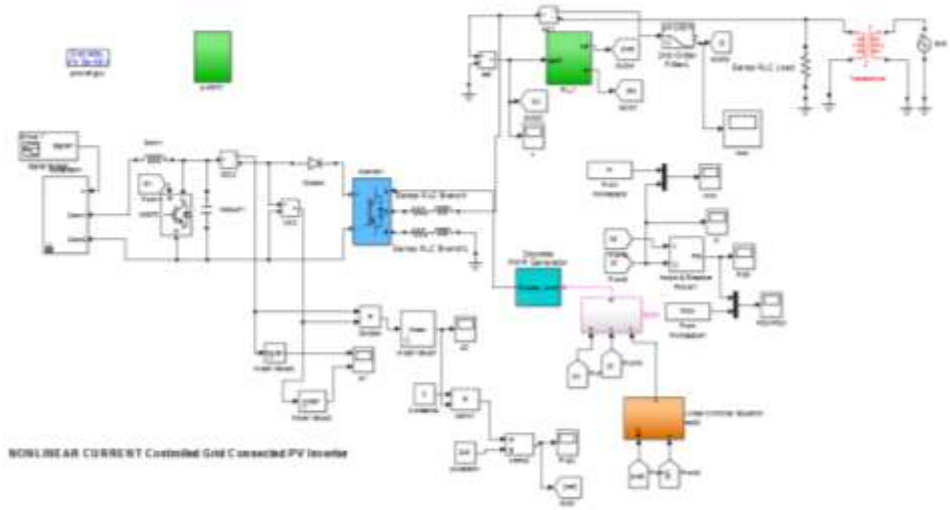


Fig 8 Simulaton model of Non-linear controller at Standard atmospheric conditions

Case 1: Controller Performance under Standard Atmospheric Conditions:

At this stage, the system is simulated under standard atmospheric condition in which the solar irradiation is considered as and the temperature as 298 K. At this condition, the output power of the PV unit from which it can be seen that there are some fluctuations due to the nonlinear characteristics of the PV system. Here comparison is shown in figure 9(d).

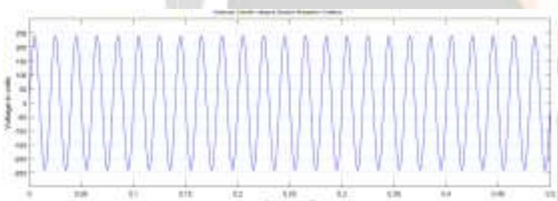


Fig 9(a)

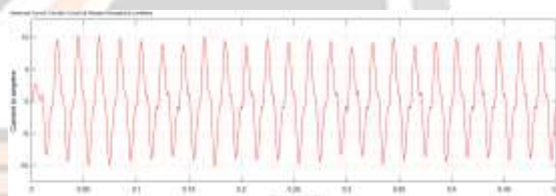


Fig 9(b)

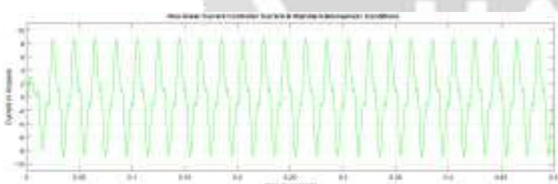


Fig 9(c)

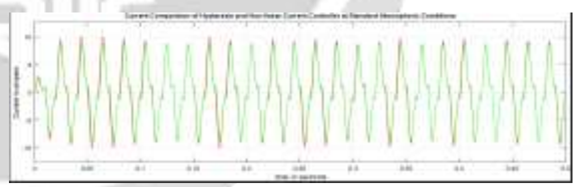


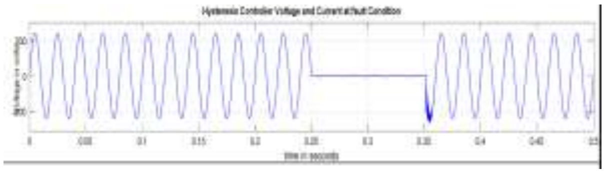
Fig 9(d)

Fig 9(a) and Fig 9(b) Hysteresis controller grid voltage and current at Standard Atmospheric conditions

Fig 9(c) Hysteresis Current at standard atmospheric condition **Fig 9(d)** Non linear current at standard atmospheric condition

Case 2: Controller Performance during Fault:

A line-to-ground fault is considered at an instance at the terminal of PV unit. When such faults are applied, PV units will not supply any power into the grid and load. Under this case study, the performance of the proposed controller is shown in Fig 10(a)-(d) from where it can be seen that the PV unit is not injecting any current into the grid from 0.25 to 0.35 s as the fault is applied for this period. The proposed controller maintains the post-fault steady state as soon as the fault is cleared but with the hysteresis controller the system becomes unstable.



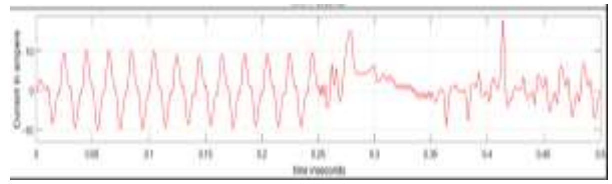
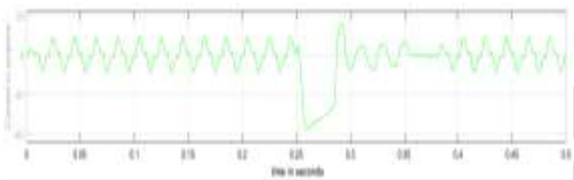


Fig 10(a) **Fig 10(b)**

Fig 10(a) and 10 (b) Hysteresis Current Controller Voltage And Current During Fault Condition



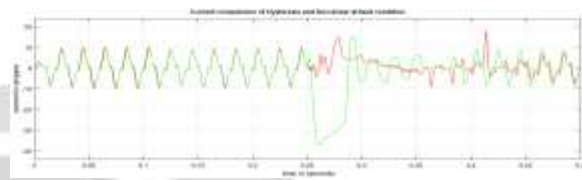


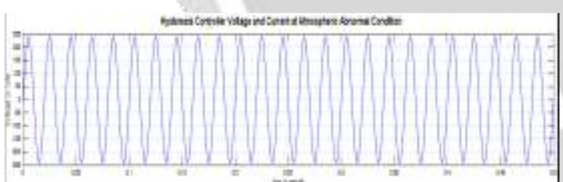
Fig 10(c) **Fig 10(d)**

Fig 10(c) Non Linear Current Controller Current during fault condition

Fig 10(d) Current Comparison of Hysteresis and Non Linear current controller during fault condition

Case 3: Controller Performance under Changing Atmospheric Conditions:

In a practical PV system, the atmospheric condition changes continuously for which there exists variations in the cell's working temperature and solar irradiation. Fig 11 shows the performance of the proposed current controller with changes in atmospheric conditions. From Fig 11, it can be seen that the PV system operates under standard atmospheric conditions from 0. to 0.5 s. But the irradiation changes from 1000 to 700 w/sq.m at 0.2 s and weather remains cloudy, i.e. the PV system is shaded until 0.2s to 0.35s. At this stage, the amount of power delivered to the grid will be changed and the MPPT will select a different MPP, but the grid voltage will be the same. After 0.35 s, with the proposed controller, the non linear current controller grid current (green line) is similar to its previous value as the system again operates at standard atmospheric conditions.



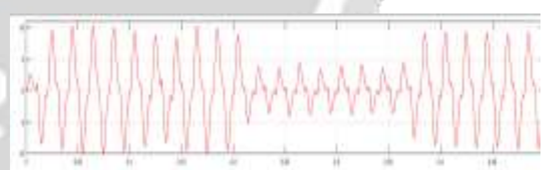
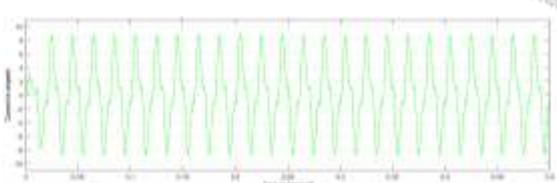


Fig 11(a) **Fig 11(b)**

Fig 11(a) and (b) Hysteresis Current Controller Voltage And Current At Changing Atmospheric Condition



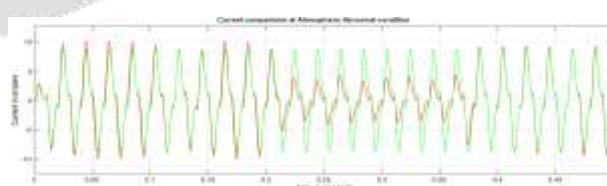


Fig 11(c) **Fig 11(d)**

Fig 11(c) Non Linear Current Controller Current At Changing Atmospheric Condition

Fig 11(d) Comparison of Hysteresis Current And Non–linear Controller Current At Change In Atmospheric Condition

5. CONCLUSION

A partial feedback linearizing nonlinear current control scheme was presented to improve the dynamic performance of a single-phase grid-connected PV system with changes in atmospheric conditions, variations in load conditions, and faults on different parts of the system. All the possible nonlinearities are very well canceled by the proposed controller designed approach by transforming the PV system into a reduced order linear system with stable internal dynamics. The injected current into grid is controlled to ensure the operation of the PV system at the MPP. Future work will deal with the extension of the proposed method by considering some mismatches within the PV model and implementation on a laboratory-based system. A review on various current control techniques/schemes has been discussed here & it is found that nonlinear current control scheme, presented & validated using MATLAB simulation is more efficient compared to hysteresis current control and other controlling schemes under various conditions. The project work is supported with results obtained in MATLAB simulation through waveforms.

5.1 Future Scope-

The proposed scheme achieves satisfactory results shown through simulation & analysis. PV systems range from distributed, residential, and commercial rooftop or building integrated installations, to large, centralized utility scale photovoltaic power stations. This scheme will help in mitigating power quality issues resulting from large scale penetration of PV system into small or micro grids. Single phase grid connected photovoltaic systems would play major role in increasing small scale distributed power generation & give confidence in solar cell power generation category.

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