ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

Nonlinear Current Controller Using Partial Feedback Linearization for Grid Connected Photovoltaic Systems

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ABSTRACT**:** Due to the concern about the climate change and sustainable electrical power supply, the world has now given more attention to renewable resources, and among them solar photovoltaic systems have proved to be a promising energy source. So efficient techniques are essential to deliver maximum power with changes in atmospheric conditions such as partial shading of the PV cells. A new nonlinear current controller using partial feedback linearizing technique has been presented in this paper which overcomes the problems of conventional PI controllers. An energy-based Lyapunov function is used to analyse the stability of internal dynamics of a PV system. The Matlab/Simulink simulation of the grid connected PV system with the proposed controller shows its efficiency.

KEYWORDS: Current Controller, Renewable energy, Grid connected photovoltaic systems, partial feedback linearization, maximum power point tracking.

I.INTRODUCTION

Due to the global awareness on the importance of energy savings and of energy efficiency, the use of renewable energy in the production of electricity has become popular all over the world. Out of the different sources of renewable energy, the photovoltaic system seems to be most promising energy source. PV installations are increasing now due to their relatively small size and noiseless operation [1]. Due to the feed-in-tariff and the reduction of battery cost, grid connected PV systems has gained popularity now-a-days. Major concerns of integrating PV into the grid are stochastic behaviours of solar irradiations and the interfacing of inverters with the grid. Efficient control schemes are essential to deliver maximum power with changes in atmospheric conditions.

As intermittent PV generation varies with changes in atmospheric conditions and due to the high initial investment and reduced life time of PV system as compared to traditional sources, it is essential to extract maximum power from PV systems. For this proper controllers have to be included, to achieve the desired performance under disturbances like changes in atmospheric conditions, changes in load demands or external faults within the system. This can be performed by regulating the switching signal of the inverter, i.e., if a proper controller is applied through the inverter switches. The current controlling techniques are intended for providing stability, low steady state error, fast transient response and low harmonic distortion. There are linear current controllers such as PID, PI, PR, Repetitive controllers etc. and nonlinear controllers such as predictive, deadbeat, hysteresis controllers etc. [2]. Linear controllers provide satisfactory operation only over a fixed set of operating points as the system is linearized at an equilibrium. This can be solved by using nonlinear controllers. But most of the nonlinear controllers are difficult in implementing.

Grid connected photovoltaic systems suffer from nonlinear behaviours due to the variation of solar irradiance and nonlinear switching functions of the inverters. For controlling such non linear systems, first we can make the system linear, and then control it with any linear techniques. Feedback linearization is a straight forward way to design nonlinear controller since it transforms a nonlinear system by cancelling the inherent non linearities within the system and then, linear controllers can be employed to design the controller for linearized system. Exact feedback linearization has been used to design controller for a three phase Photovoltaic system in [3] and [4], in which the system is transformed into a dq-frame through a straightforward way. But in the case of a single-phase grid-connected PV

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

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system, the dq transformation is not straightforward to that of a three-phase system. A grid connected PV system can be partially linearized. When the system is partially linearized, exact linearization is no more applicable.

The main aim of this paper is to design an efficient current controller through partial feedback linearization to control the current injected into the grid. It also includes the stability of internal dynamics through the formulation Lyapunov function and the calculation of sinusoidal reference current. In [5], the PI controller keeps the output current sinusoidal provides fast dynamic responses under rapidly changing atmospheric conditions. The difficulty of using a PI controller is the necessity of tuning the gain with changes in atmospheric conditions [6]. This problem has also been solved in this paper. The performance of the proposed current control scheme is also investigated in this paper under changes in atmospheric conditions.

II. PV SYSTEM MODELING

A. PV cell modeling

A PV cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon. Ideal solar cell is a current source in which current produced by the solar cell is proportional to the solar irradiation intensity falling on it.

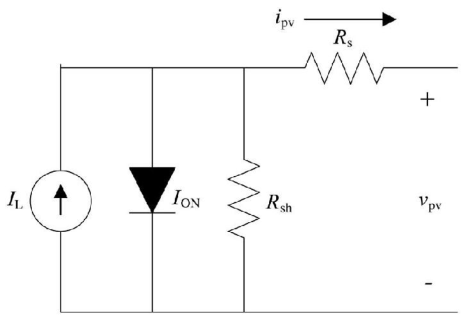

Fig. 1. Equivalent circuit diagram of PV cell

An equivalent circuit diagram of a PV cell is shown in fig.1. I_L is the light generated current source, R_{sh} is shunt resistance R_s is series resistance and I_{ON} is the current through the parallel diode.

$$I_{ON} = I_s \left[e^{[\alpha(v_{pv}+R_s\, i_{pv})]} - 1\right] \tag{1}$$

Where α is a constant which is equal to $\frac{q}{AkT_C}$, $k = 1.3807 \times 10^{-23} JK^{-1}$ is Boltzmann's constant,

$q = 1.6022 \times 10^{-19} C$ is the charge of electron, T_C is the cell's working temperature in Kelvin, A is the p–n junction ideality factor whose value is between 1 and 5, v_{pv} is the output voltage and I_s is the saturation current.

$$I_s = I_{RS} \left[\frac{T_C}{T_{ref}}\right]^3 e^{\left[\frac{qE_g}{Ak}\right]\left(\frac{1}{T_{ref}}-\frac{1}{T_C}\right)} \tag{2}$$

Where I_{RS} is the reverse saturation current of the cell at the reference temperature and solar irradiation, E_g is the band-gap energy of the semiconductor used in the cell and T_{ref} is the reference temperature of the cell. By applying Kirchhoff's current law (KCL) in Fig. 1, the output current (i_{pv}) generated by the PV cell can be written as

$$i_{pv} = I_L - I_{ON} - \frac{v_{pv}+R_s\, i_{pv}}{R_{sh}} \tag{3}$$

The light generated current I_L is given by:

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ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

$$I_L = \left[I_{sc} + k_i(T_C - T_{ref})\right]\frac{s}{1000} \quad (4)$$

Where I_{sc} is the short-circuit current, s is the solar irradiation and k_i is the cell's short-circuit current coefficient.

B. PV array modeling

Since the output voltage of a PV cell is very low, a number of PV cells are connected together in series in order to obtain higher voltages. They are 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, considering N_s as the number of cells in series and N_p as the number of modules in parallel, can be written as:

$$i_{pv} = N_p I_L - N_p I_s \left\{ e^{\left[\alpha\left(\frac{v_{pv}}{N_s} + \frac{R_s\, i_{pv}}{N_p}\right)\right]} - 1 \right\} - \frac{N_p}{R_{sh}}\left(\frac{v_{pv}}{N_s} + \frac{R_s i_{pv}}{N_p}\right) \quad (5)$$

C. Single-Phase Grid-Connected PV System Modeling

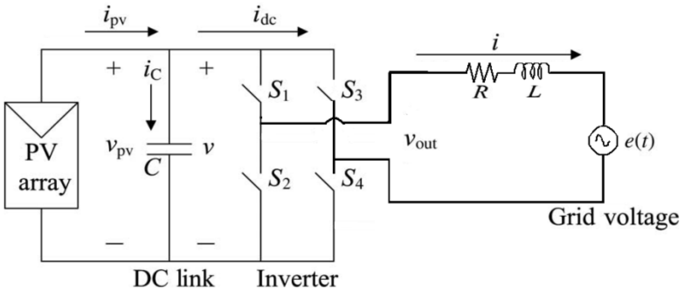

Fig. 2. Equivalent circuit diagram of single-phase grid-connected PV system

Fig 2 shows the schematic diagram of a single-phase grid-connected PV system where R is the line resistance, L is the combination of filter and line inductance, S_1, S_2, S_3 and S_4 and are the four switches of the inverter, i is the current injected into the grid, and $e(t) = V_m \sin \omega t$ is the grid voltage where V_m is the maximum value of the grid voltage, $\omega = 2\pi f$ is the angular frequency, and f is the grid frequency.

When S_1 and S_4 are ON, and S_2 and S_3 are OFF in Fig. 2,

$$\dot{v} = \frac{1}{C}\left(i_{pv} - i\right) \;, \dot{i} = \frac{1}{L}(v - Ri - e) \quad (6)$$

When S_1 and S_4 are OFF, and S_2 and S_3 are ON in Fig. 2,

$$\dot{v} = \frac{1}{C}\left(i_{pv} + i\right) \;, \dot{i} = \frac{1}{L}(v + Ri - e) \quad (7)$$

Now by applying averaging technique [7], (6) and (7) can be written as

$$\dot{v} = \frac{1}{C}\left(i_{pv} - iu(t)\right) \;, \dot{i} = \frac{1}{L}(vu(t) - Ri - e) \quad (8)$$

Where u is the control input with a possible range of ± 1 and i is the output variable. Equation (8) represents the complete mathematical model of a single-phase grid-connected PV system which is nonlinear. Based on this model, control strategy is presented in this paper using partial feedback linearization technique.

III. PARTIAL FEEDBACK LINEARIZATION

Feedback linearization cancels the nonlinearities in a nonlinear system so that closed loop dynamics is in a non linear form. When feedback linearization transforms a non linear system into partially linearized system, it is called partial feedback linearization.

The mathematical model of a single-phase grid-connected PV system can be expressed as the general nonlinear system as:

$$\dot{x} = f(x) + g(x)u \;, \quad y = h(x) \quad (9)$$

Where:

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ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

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

This nonlinear system (9) can be linearized using feedback linearization. Consider the following nonlinear coordinate transformation:

$$z = \left[hL_f h(x) \ldots L_f^{r-1} h(x)\right]^T \tag{10}$$

Where $L_f h(x) = \left(\partial h/_{\partial x}\right) f(x)$ is the Lie derivative of *h(x)* along *f(x)* [8] , r is known as the relative degree of the system corresponding to the output function. This transforms the nonlinear system (9) with the state vector *x* into a linear dynamic system with the state vector *z*. When r<n, we can perform only partial feedback linearization. The partial linearizability of the PV system represented in (9) can be obtained by calculating the relative degree corresponding to the output function, $h(x) = i$.

$$L_g h(x) = L_g L_f^{1-1} h(x) = \frac{v_{pv}}{L} \tag{11}$$

From this it's clear that r=1. As n=2 here, we thus found that r is less than n, i.e., r<n. So, the system is partially linearizable for the chosen output function.

IV.CONTROLLER DESIGN

The nonlinear current controller proposed in this paper is a combination of partial feedback linearization and PI controller. The steps to obtain control law are discussed in this section.

A. Nonlinear Coordinate Transformation and Partial feedback Linearization:

For the single phase grid connected system we can choose the non linear coordinate transformation as:

$$\widetilde{z_1} = \widetilde{\phi_1}(x) = h(x) = i \tag{12}$$

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

$$\widetilde{Z_1} = \frac{\partial h(x)}{\partial x}\dot{x} = L_f h(x) + L_g h(x) u \tag{13}$$

So, for the system considered here,

$$\dot{\widetilde{Z_1}} = \frac{-R_i - e}{L} + \frac{v}{L} u \tag{14}$$

It can be written as the following linear control input:

$$\tilde{v} = \frac{-R_i - e}{L} + \frac{v}{L} u \tag{15}$$

B. Stability of Internal Dynamics of a Grid-Connected PV System:

Before designing and implementing controller through partial feedback linearization, it is essential to check the stability of internal dynamics of the system. Lyapunov functions are the functions that are applicable to analyse the stability of the equilibrium states for dynamical systems. Lyapunov function is defined as [9]: If a function *V(x)* is positive definite and if its time derivative $\dot{V}(x)$ along any state trajectory of the system $\dot{x} = f(x)$ is negative definite, i.e., *V(x)<0* , then *V(x)* is said to be a Lyapunov function.

From the perspective of the dynamical system stability, there exists a Lyapunov function for each dynamical system if the system is inherently stable, i.e., the internal dynamics of the system is stable. Since the main aim of the proposed controller is to track the reference current efficiently, i.e., with zero tracking error, the Lyapunov function can be constructed by considering only the current equation. In this case, the energy function for the purpose of controlling current can be written as:

$$V = \frac{1}{2} L i^2 \tag{16}$$

The derivative of (16):

$$\dot{V} = Lii \tag{17}$$

Substituting i from (8),

$$\dot{V} = viu(t) - i^2 R - ei \tag{18}$$

 DOI: 10.15662/ijareeie.2015.0408077

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Using the value *u(t)* from (15),

$$\dot{V} = \tilde{v}i \tag{19}$$

$\tilde{v}$ includes the difference between the reference current and instantaneous current and the purpose of the proposed control scheme is to make this difference as zero. Therefore:

$$\tilde{v} = 0 \tag{20}$$

Therefore:

$$\dot{V} = 0 \tag{21}$$

Thus, we found that the derivative of the energy function V is zero, also we know that the equation (16) is always positive. So this indicates that (16) is a Lyapunov function for the considered PV system and the internal dynamics of the system is stable. Therefore, the partial feedback linearization can be used to design current controller for a single-phase grid connected PV system.

C. Derivation of the Control Law:

From (15), the control law can be obtained as follows:

$$u = \frac{1}{v}(L\tilde{v} + Ri + e) \tag{22}$$

Where $\tilde{v}$ is the new linear control input and can be designed by any linear control technique. Here a PI controller is used. The following PI controller is considered to track the output:

$$\tilde{v} = K_P(i_{ref} - i) + K_I \int_0^t (i_{ref} - i)dt \tag{23}$$

Where K_P is the proportional gain and K_I is the integral gain. Here, these values are set as: $K_P = 2P_{ref}$ and $K_I = P^2{}_{ref}$. In this case, the gains of the PI controllers depend on the reference value of the power. This reference value is calculated from the MPPT as shown in Section V. Thus, the gain of the controller will be updated automatically with changes in atmospheric conditions.

V. CALCULATION OF REFERENCE VALUE OF CURRENT AND POWER

The Maximum Power Point Tracking (MPPT) technique is used in PV systems to track maximum power point (MPP) at all environmental conditions and then force the system to operate at that MPP. Here Perturb and Observe (P&O) method of MPPT is used. It involves perturbation in the voltages of PV array. If there is an increase in power ie, irradiation level, subsequent perturbation is kept same to reach MPP. If there is a decrease in power, perturbation is reversed. Process is repeated periodically until MPP is reached [10].

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

$$P_{ref} = v_{pv}i_{pv} \tag{24}$$

It is also the maximum power which is supplied to the grid. Therefore:

$$P_{Grid} = ei = V_m \sin\omega t \times I_m \sin\omega t = \frac{V_m I_m}{2}(1 - \cos 2\omega t) \tag{25}$$

Average power into the grid:

$$P_{av} = \frac{2}{T}\int_0^{\frac{T}{2}} \frac{V_m I_m}{2}(1 - \cos 2\omega t)dt = \frac{V_m I_m}{2} \tag{26}$$

The MPPT controls average power to follow the reference power. At reference power, the magnitude of reference current wil be I_{refm}. So,

$$P_{ref} = \frac{V_m I_{refm}}{2} \tag{27}$$

The reference current into the grid,

$$I_{ref} = \frac{2P_{ref}}{V_m} sin\,\omega t \tag{28}$$

Where ωt is obtained using PLL (phase locked loop).

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Vol. 4, Issue 8, August 2015

VI.PERFORMANCE EVALUATION

The implementation block diagram of a partial feedback linearizing controller for a single-phase grid-connected PV system is shown in Fig. 3. The magnitude of the reference current for the linear controller is obtained from the MPPT and the angle is extracted from the grid current using a PLL. Finally, the control input is implemented through the inverter switches using a pulse width modulation (PWM) technique where the switching frequency of the inverter is considered as 10 kHz.

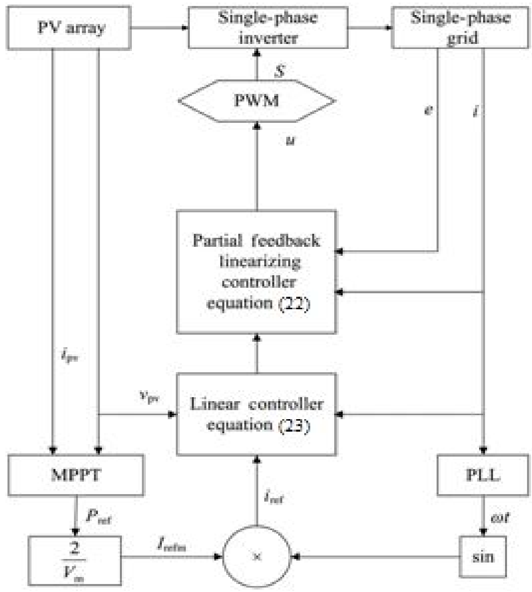

Fig. 3. Implementation block diagram of partial feedback linearizing controller.

The performance of the designed controller is evaluated on the simple system as shown in Fig. 2. The simulations are done in MATLAB/SIMULINK. To simulate the performance, a PV array consisting of five strings, characterized by a rated current of 4.79 A, is connected in parallel. Each string is subdivided into five modules, characterized by a rated voltage of 35.5 V, and connected in series. Thus, the total output voltage of the PV array is 177.5 V, the output current is 23.95 A, and the total power is 4.251 kW. The value of the dc-link capacitor is $400\mu F$. The line resistance is 0.1Ω 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 changing atmospheric conditions as follows.

The system is simulated atmospheric conditions in which the standard solar irradiation is considered as $1\ kW/m^2$ and the standard temperature as 298 K. In a practical PV system, the atmospheric conditions change and thus cell's working temperature and solar irradiation will get changed.

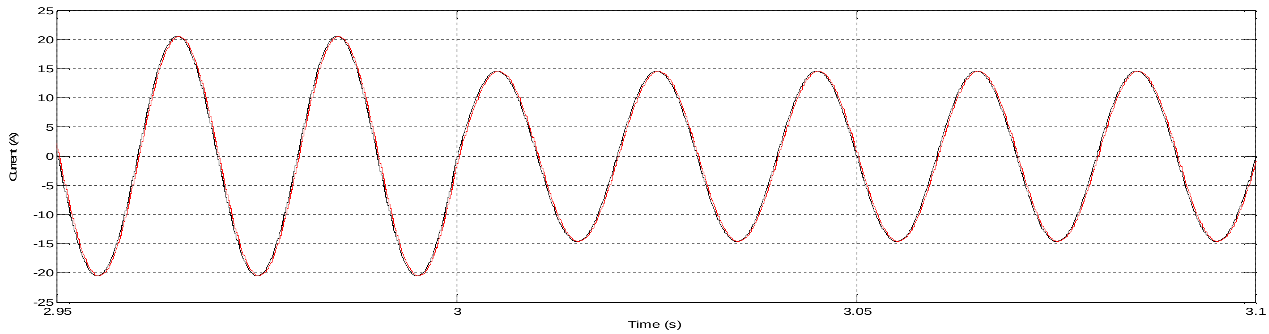

Fig. 4. Performance of PI controller (conventional controller). [Black line – Reference current, Red line – Grid current]

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

Fig. 4 and Fig. 5 show the performance of the PI controller and proposed current controller respectively with changes in atmospheric conditions. From these figures, it can be seen that the PV system operates under standard atmospheric conditions from 2.95 to 3 s. But the irradiation changes from 1to 0.75 kW/m^2 at time = 3s.

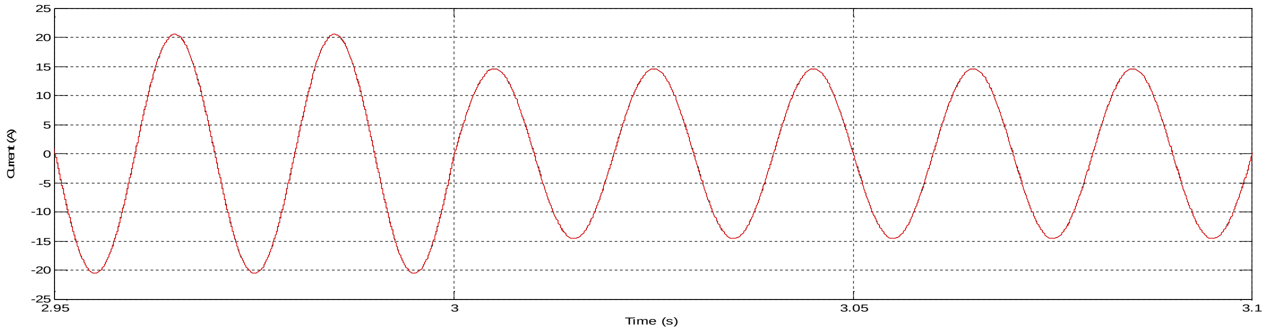

Fig. 5. Performance of proposed controller. [Black line – Reference current, Red line – Grid current]

From the simulation results, it can be clearly seen that the proposed current controller can track the reference current accurately than the conventional PI controller.

VI.CONCLUSION

A non linear current controller using partial feedback linearization was proposed in this paper to enhance the dynamic performance for a single phase photovoltaic system with changes in atmospheric conditions. Actually, this controller is a combination of a linear and partial feedback linearizing controller. It solves the problem of the conventional PI controller to tune its gain with atmospheric changes, as here the gain of the proposed controller gets updated automatically with changes in atmospheric conditions. The current injected into the grid is controlled to ensure the operation of the PV system at the maximum power point. From the simulation results, it is clear that the controller performs satisfactorily as compared to a conventional PI controller.

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