Rapid MPPT of Grid-Tied Photovoltaic System with Quadratic Converter using Sliding Mode-Like Controller

Umesh K. Shinde*‡, Sumant G. Kadwane**, S. P. Gawande**

*Department of Electrical Engineering, Bhivarabai Sawant College of Engineering and Research, Pune, India

**Department of Electrical Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, India

(ukshinde@yahoo.com, sgkadwane@gmail.com, spgawande_18@yahoo.com)

‡ Corresponding Author; Umesh K. Shinde, Bhivarabai Sawant College of Engineering and Research, Narhe, Pune, India,

Tel: +90 99755 62383, ukshinde@yahoo.com

Received: 25.04.2017 Accepted:07.08.2017

Abstract- Two stage micro-inverters are preferred for low power, low input voltage, single-phase grid-tied photovoltaic systems. In this paper, a sliding mode-like controller applied to the low power, grid-tied Photovoltaic (PV) system with front end quadratic converter has been investigated for maximum power point tracking (MPPT). Quadratic converter for front end ensures very high gain when the input is supplied by the low voltage single PV module. The primary advantage of this control configuration is the improved dynamic response, particularly for rapidly varying environmental conditions. Owing to improved dynamic response, the overall efficiency of the system is higher and ripple on PV terminals and DC link capacitor is minimum. This paper presents the effectiveness of the proposed controller using MATLAB-based simulation results, which are superior as compared to popular Incremental Conductance method.

Keywords Photovoltaic system, maximum power point tracking (MPPT), quadratic converter, sliding mode controller.

1. Introduction

Due to limited availability of fossil fuels, worldwide more focus is on renewable energy sources like wind and solar. Among all renewable energy sources, solar energy is getting more consideration, because of its ample availability. PV cells directly convert solar energy into electrical energy. Multiple PV cells are connected in series/parallel to form a PV panel. But, the characteristics of PV cell are highly nonlinear in nature, and it depends on the solar insolation and ambient temperature. Due to nonlinear nature of PV cell, to maximize the output power, an external mechanism for maximum power point tracking (MPPT) is required [1]. In recent year, grid connected PV systems are getting popular as it does not require battery setup to ensure MPPT and high efficiency because of less power conversion stages. The grid-tied PV systems are normally categorized into single stage conversion systems and two stage conversion systems. In single stage conversion system, PV output which is at sufficiently high voltage is directly connected to the grid through an inverter. Whereas in two stage conversion system, since PV voltage is less, an additional front end DC-DC converter is required in order to obtain desired output. For micro-inverter applications, normally a single PV panel of power less than 250W is used. Since the output voltage of single panel is less, single switch boost converter is not sufficient to get required gain. For such applications, the quadratic converter can be employed. In this paper, a single switch quadratic converter is employed at the front end to get required voltage ratio.

Different techniques to track the maximum power point (MPP) have been addressed in the literature. Among these methods, Perturb & Observe (P&O) method and Incremental Conductance (INC) method are regularly used due to their simple algorithm and low-cost implementation [1], [2]. However, these methods fail to perform during rapid varying environmental condition. Other improved methods are also investigated by researchers to progress the MPPT response of the system and minimize the oscillations at MPP [3]-[6]. Review of different MPPT techniques is also reported by

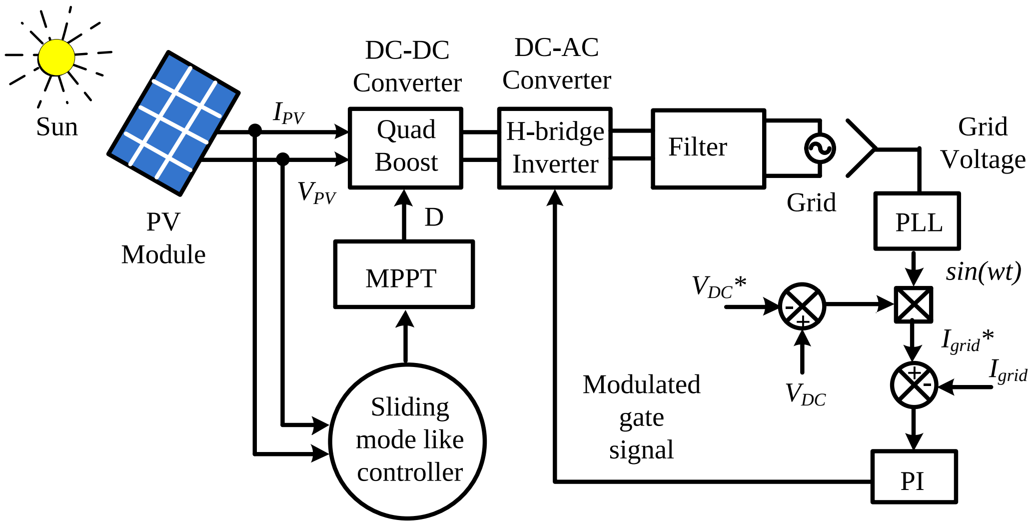


Fig. 1. Scheme of single-phase grid tied PV system using proposed sliding mode-like controller.

researchers [7]-[9]. The performance of grid-tied PV system is judged by dynamics of MPPT controller. Control algorithm implementation for grid-connected PV system are presented in various literature [10]-[13].

Sliding Mode Control (SMC) which is known for inherent fast response and stability against parameter and load uncertainties [14], can be used for MPPT under rapidly varying environmental conditions [15]. Output-based sliding mode (SM) approach applied to boost converter in the standalone system is presented in [16], which does not require state model of the converter. Various sliding mode control strategies are presented in the literature [17]-[21]. In this approach, normally P&O or other MPPT algorithms are used to derive the reference voltage or current quantity. SMC is applied to regulate PV voltage or current as per this reference quantity. A hybrid analog-digital implementation of SMC for a DC-DC boost synchronous converter for PV application is presented in [22], which is further applied to synchronous SEPIC converter [23]. A double integral SMC-based MPPT is proposed for the stand-alone photovoltaic system in [24]. A dual surface SMC controller for PV system is presented in [25], which uses ripple domain search MPPT algorithm for generating reference quantity.

SMC for MPPT of PV panel has been investigated using different DC-DC converters and DC-AC inverters also. SMC for MPPT of PV panel, using quadratic boost converters with grid feed inverter has been investigated in very few literature [26], [27]. In this paper, output-based SM-like controller applied to the quadratic converter for grid connected system has been presented. As compared to [16], this paper suggests the use of PV current instead of the inductor current, which reduces the need for the high bandwidth current sensor. The general block diagram for grid-tied micro-inverter, using SM-like controller for MPPT of PV system is shown in Fig. 1. PV panel is connected to the grid feed inverter through the front end quadratic converter. Two control blocks are required, one for DC side and second for AC side. The objective of DC controller is to extract MMP from PV panel. The proposed DC side controller need to measure only PV voltage and PV current, which eliminates the need for high bandwidth sensors. The objective of AC side controller is, to control the DC link voltage and feed available active power to the grid.

This paper is organized as: Section II presents the mathematical model of PV cell. Proposed SM-like control approach for MPPT is explained in section III. Application of proposed SM-like controller for two stage grid-tied system is elaborated in section IV. Section V provides MATLAB-based simulation results of the proposed system for rapidly varying environmental conditions, followed by a summary of the work presented in last section VI.

2. Mathematical Model of PV Cell

The commonly used, single diode-based, PV cell model which has been reported in the literature is shown in Fig. 2. The equation for PV output current I is,

$$I = I_{ph} - I_s\left[\exp\left(\frac{q(V+IR_s)}{AkT}\right)-1\right] - \frac{(V+IR_s)}{R_{sh}} \quad (1)$$

The equation for photovoltaic current I_{ph}, reverse saturation current I_S, reverse saturation current at reference temperature I_{rr} are follows:

$$I_{ph} = [I_{scr} + k_i(T_c - T_r)]\frac{S}{1000} \quad (2)$$

$$I_s = I_{rr}\left(\frac{T}{T_r}\right)^{3/A} \exp\left(\frac{V_g q}{Ak}\left(\frac{1}{T_r}-\frac{1}{T_c}\right)\right) \quad (3)$$

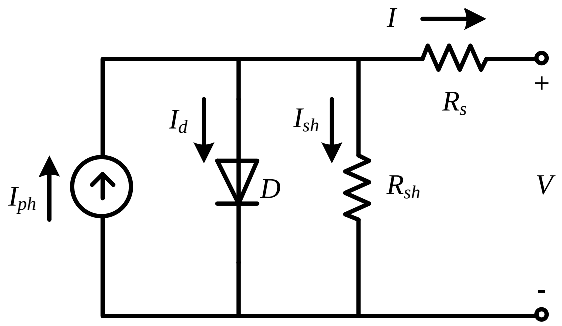


Fig. 2. Equivalent circuit of PV cell.

$$I_{rr} = \frac{I_{scr}}{\exp\left(\frac{qV_{ocr}}{AkT_r} - 1\right)} \quad (4)$$

where I_{ph} is photovoltaic current (A), I_S is reverse saturation current (A), I_{scr} is the cell short circuit current at reference temperature and insolation (A), k_i is the short circuit current temperature coefficient, T_c is the cell temperature (K), T_r is the cell reference temperature (K), S is the solar insolation in (W/m^2), V_{ocr} is open circuit voltage at reference temperature (V) and other symbols have their usual meanings.

A mathematical model of PV cell is defined by equations (1)-(4), are adapted for simulation work. Table I shows the parameters of the PV module used for simulation in MATLAB software. Nature of Power vs Voltage characteristics of this PV module, for different insolation, are presented in Fig. 3(a) and for different temperature conditions are presented in Fig. 3(b).

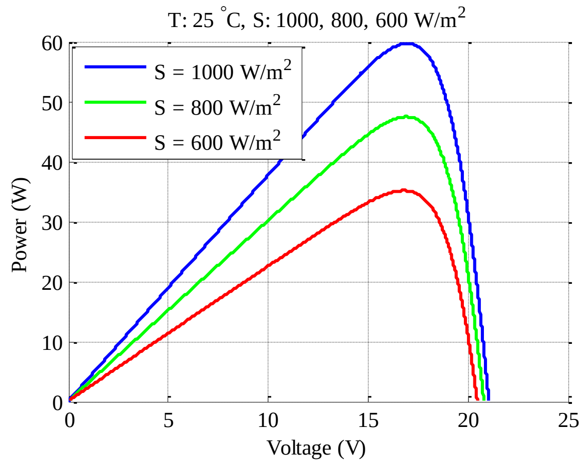
3. Sliding Mode Control Approach for MPPT

SMC is a well-established robust technique for switching converters which can be extended for MPPT of PV modules. SMC has two modes of operation. The first mode is called as approaching mode and the second mode is called as a sliding mode. In the first mode, the state trajectory of the system approaches to a pre-defined manifold called as a sliding function in finite time. Whereas in sliding mode, the state trajectory of the system is restricted to the sliding line or surface and is driven to the origin which normally corresponds to the steady state position. The sliding line is a line in the phase plane passing through the origin, which represents a stable operating point for converters and is the main control input. This sliding line splits the phase plane into two regions, which are specified for different (ON/OFF) switching states. Selected switching function, directs the phase trajectory towards the sliding line.

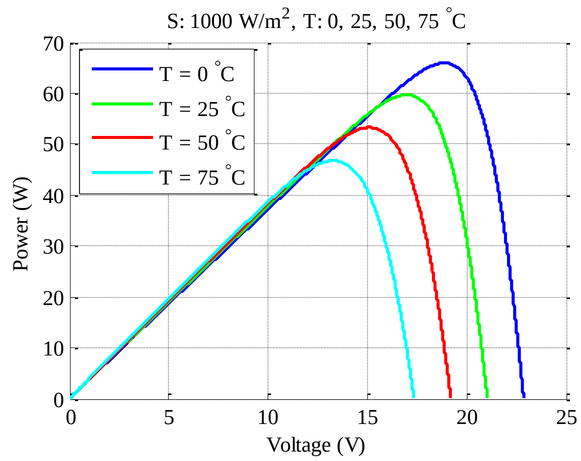
For the design of SM controller, one needs to prepare the state model of selected converter. There is one more approach for SMC called as output-based SMC, which requires the knowledge of output parameters only [14]. The

Table 1. PV Module Parameters

Parameters	Values
Reference Temperature (T_1)	25 ^0C
Number of series cells (N_s)	36
Module open circuit voltage at reference temperature (V_{ocr})	21.06 V
Module short circuit current at reference temperature (I_{scr})	3.8 A
Short circuit current temperature coefficient (k_i)	0.0024
PN junction ideality factor (A)	1.2
Band gap voltage of the semiconductor (V_g)	1.12 eV



(a)



(b)

Fig. 3. Characteristic curves of PV module (a) P-V characteristics for different insolation (b) P-V characteristics for different temperature

proposed controller applied to the quadratic converter for MMPT in this paper uses this output-based SMC approach.

The SMC approach presented in [16], with the proposed modification are presented as follows. The sliding surface is selected as $\partial P_{pv} / \partial I_{pv} = 0$, which along with switching function guarantees to produce maximum power output persistently.

$$\frac{\partial P_{PV}}{\partial I_{PV}} = \frac{\partial I^{2}{}_{PV} R_{PV}}{\partial I_{PV}} = I_{PV}(2R_{PV} + I_{PV}\frac{\partial R_{PV}}{\partial I_{PV}}) = 0 \tag{5}$$

where $R_{pv} = V_{pv} / I_{pv}$ is the load resistance connected to the PV terminals, I_{PV} is the PV current. The non-trivial solution of equation (5) is:

$$\sigma \underline{\underline{\Delta}}\, 2R_{PV} + I_{PV}\frac{\partial R_{PV}}{\partial I_{PV}} = 0 \tag{6}$$

In reference [16], the author suggested considering inductor current I_L, since PV current I_{PV} and inductor current I_L are identical. But due to the presence of bulk capacitor, PV current I_{PV} and inductor current I_L are different. Hence it is proposed in this paper, to consider PV current I_{PV} for implementation of the sliding surface. Since at MPP, PV current is constant, a low bandwidth sensor is sufficient for measurement of PV current.

From Fig. 4, in the region left to MPP, the operating point approaches to MPP as the duty cycle decreases. Similarly, in the region right to MPP, the operating point approaches to MPP as the duty cycle increases. Based on this observation, the duty cycle output control is selected as:

$$\delta_{new} = \begin{Bmatrix} \delta + \Delta\delta & for \;\; \sigma > 0 \\ \delta - \Delta\delta & for \;\; \sigma < 0 \end{Bmatrix}$$

The equivalent control δ_{eq} is determined from the following condition:

$$\dot{\sigma} = \left[\frac{\partial \sigma}{\partial X}\right]^{T} \dot{X} = \left[\frac{\partial \sigma}{\partial X}\right]^{T} \left(f(X) + g(X)\delta_{eq}\right) = 0 \tag{7}$$

The equivalent control as derived in [11] is,

$$\delta eq = -\frac{\left[\frac{\partial \sigma}{\partial X}\right]^{T} f(X)}{\left[\frac{\partial \sigma}{\partial X}\right]^{T} g(X)} = 1 - \frac{V_{PV} i_{L}}{V_{o}} \tag{8}$$

The value of duty cycle lies in between 0 and 1 ($0 < \delta_{eq} < 1$), the new control signal is proposed as:

$$\delta_{new} = \begin{Bmatrix} 1 & & \delta_{eq} + K\sigma \geq 1 \\ \delta_{eq} + K\sigma & for & 0 < \delta_{eq} + K\sigma < 1 \\ 0 & & \delta_{eq} + K\sigma \leq 0 \end{Bmatrix} \tag{9}$$

Equivalent control ensures the fixed frequency operation of the converter. Since the controller is an output-based controller, the same controller can be used for other DC-DC converters like single switch boost, buck, and Cuk converter, with the proper switching function.

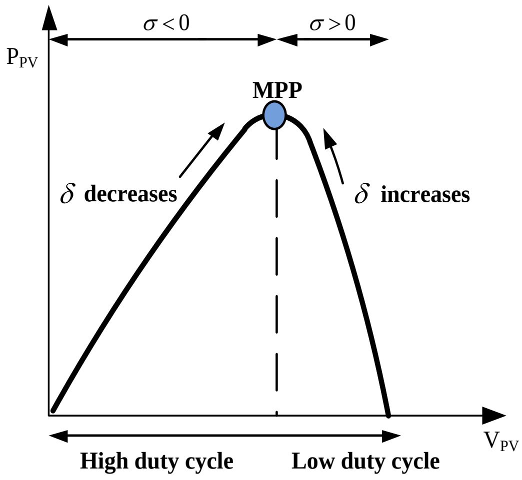


Fig. 4. Duty cycle versus operation region

4. Proposed MPPT-Based Grid-Tied System

Proposed dual stage SM-like controller-based grid-tied PV system is presented in Fig. 4. A single PV panel which is normally rated for lower open circuit voltage is connected to the quadratic converter. A bulk capacitor C_p is connected to PV panel to minimize the ripple on PV output. The value of bulk capacitor across PV panel for grid feed inverter can be calculated by using following equation.

$$C_{p} = \frac{P_{PV}}{2\omega_{g} v_{c} \hat{v}_{c}} \tag{10}$$

where P_{pv} is the average output power (W), v_c is the voltage across the capacitor (V), $\hat{v}_c$ is the allowed ripple voltage (V), and ω_g is the grid frequency (rad/sec).

For micro-inverter with quadratic converter, since the input voltage is very less, the required value of capacitor C_p is huge. But for two stage converter, as in the proposed topology, the value of output capacitor of the converter, which is connected to the DC link of the inverter, can be calculated by using above equation. Since the output voltage of the converter is greater than the input voltage, relatively less value of the capacitor is required at DC link. This converter output capacitor helps to maintain the DC link ripple within the predefined limit. A lesser value of the capacitor can be used across PV panel to reduce high-frequency ripple.

The output of the quadratic converter is connected to grid feed inverter through AC side filters. This proposed system involves two controllers, one is DC side controller and second is AC side controller. The purpose of the DC side controller has to track MPP under all changes in environmental conditions. The DC side controller should be

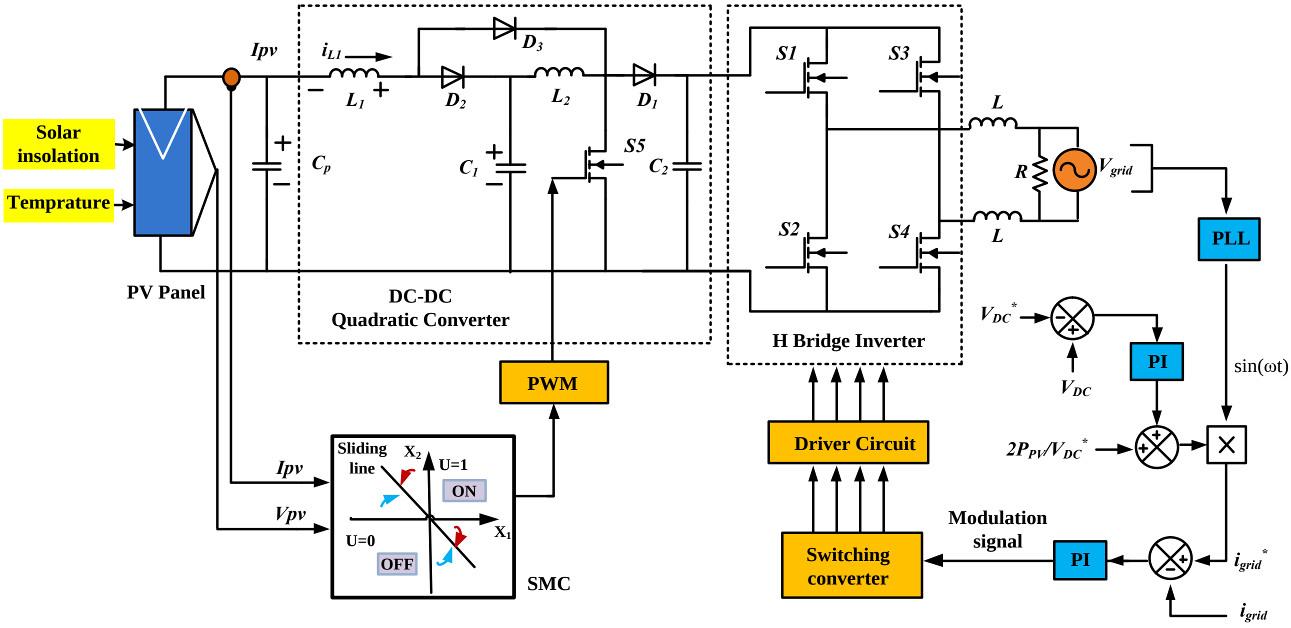


Fig. 5. Proposed single-phase grid-tied micro-inverter system.

fast enough to respond to the rapid changes in environmental conditions of insolation and temperature. Though fast changes in temperature are not expected, fast changes in insolation need to be considered for applications like roof-top PV panel mounted hybrid vehicles. The objective of AC side controller is to control the DC link capacitor voltage and also feed-forward tracked active power to the grid with lesser harmonics. The DC link capacitor voltage should be always greater than the peak voltage of the maximum value of grid AC voltage.

DC side controller measures PV voltage and PV current for implementation of MPPT algorithm. The controller calculates terminal resistance R_{PV} of PV panel from PV voltage and current. Further, it calculates values of incremental resistance ∂R_{PV} and incremental current ∂I_{PV} from recently measured values and previously measured values of PV voltage and current. The measured value of PV current I_{PV} and calculated values of ∂R_{PV} and ∂I_{PV} are used for implementation of sliding line equation.

Phase Locked Loop (PLL) in AC side controller, prepares the reference sine signal with unit amplitude and of the fundamental frequency. This reference signal is used for synchronization of inverter output current with the grid. The reference value of DC link capacitor voltage V_{DC}^* is compared with actual DC link capacitor voltage V_{DC} and this difference is fed to PI controller to maintain DC link capacitor voltage. The power supplied by PV panel and the DC link voltage are used to prepare the feed-forward signal, which is added to the output of PI controller. This feed-forward signal improves the transient performance of the DC controller.

The sum of feed-forward signal and output of the PI controller is multiplied with the reference sine signal derived from PLL to produce the reference AC current signal I_{ac}^*. This reference AC current I_{ac}^* is compared with the actual inverter output current and the error difference is fed to the current PI controller. The output of the PI controller is used as modulating signal which drives inverter switches.

5. Simulation Results

Simulation of the proposed system has been carried out in MATLAB software. The effectiveness of the proposed MPPT controller is verified by observing the dynamic response of the controller for variations in insolation and temperature conditions. A single PV panel of the power rating of 250W has been selected for simulation.

In order to demonstrate the dynamic response of the controller for rapid change in insolation, two sets of the test are conducted. Under the first test, gradual increase and decrease in insolation are carried out. And in the second test, a step increase and a decrease in insolation are carried out.

For the first test, initially, insolation and temperature are set at 1000W/m^2 and 25ºC respectively. A gradual fall in insolation from 1000W/m^2 to 600W/m^2 is applied to the PV model during 0.2sec to 0.3sec. Further, gradual rise in insolation from 600W/m^2 to 1000W/m^2 is applied during 0.4sec to 0.5sec. Fig. 6(a) shows voltage, current and power waveforms of PV panel for applied gradual fall and rise of solar insolation. There is negligible change in PV voltage, whereas PV current is directly proportional to solar insolation. PV voltage has 5% ripple, which can be further minimized by increasing the value of the bulk capacitor. This ripple has less than 2% effect on power waveform.

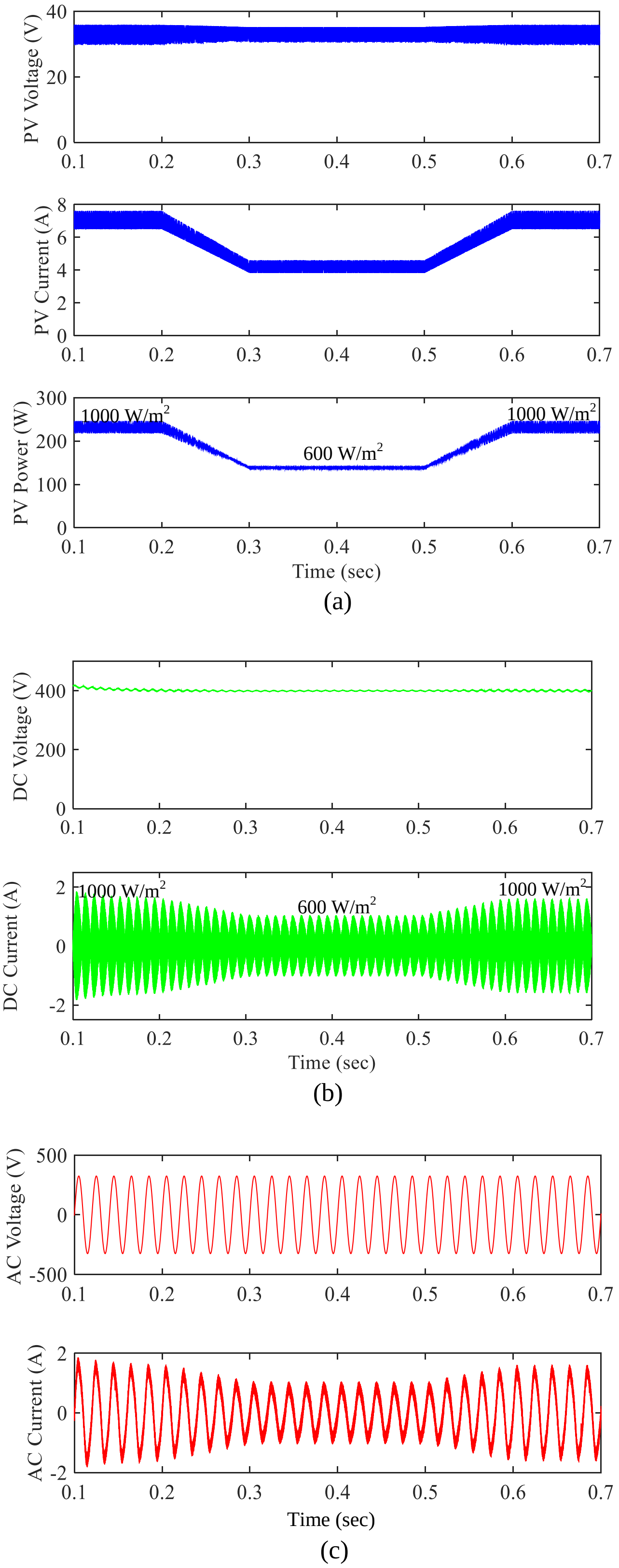


Fig. 6. Simulation results for gradual change in insolation (a) PV voltage, current and power (b) DC link voltage and current (c) AC side voltage, current and power.

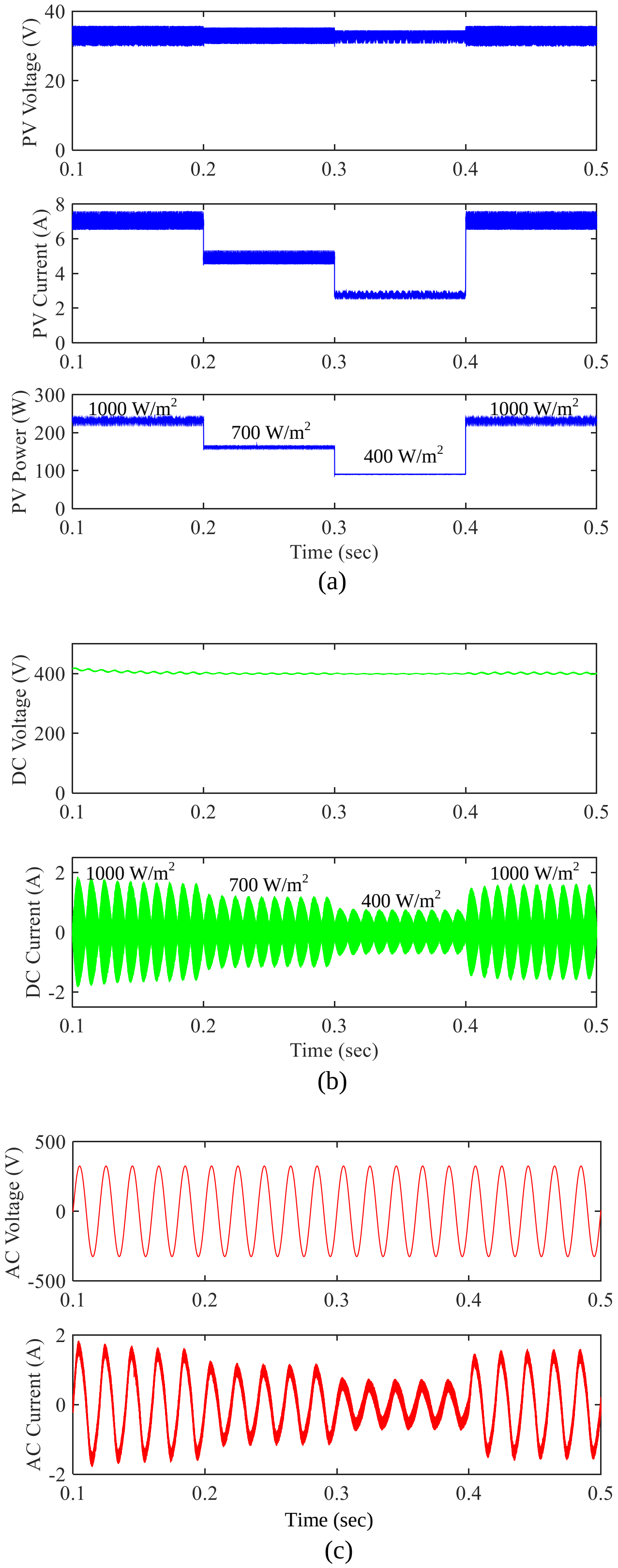


Fig. 7. Simulation results for step change in insolation (a) PV voltage, current and power (b) DC link voltage and current (c) AC side voltage, current and power.

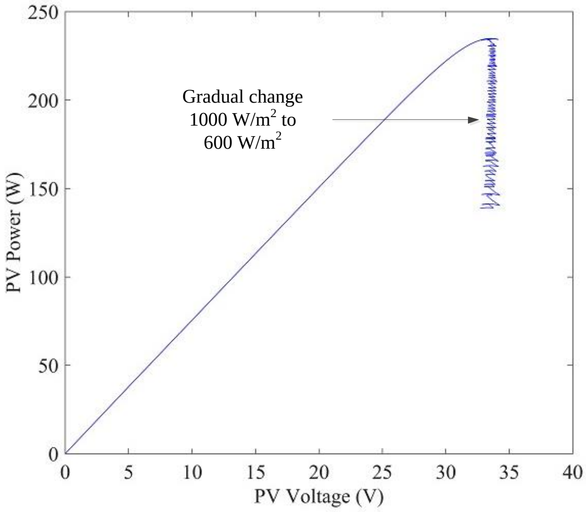


Fig. 8. P-V characteristics of PV panel for gradual changes in insolation

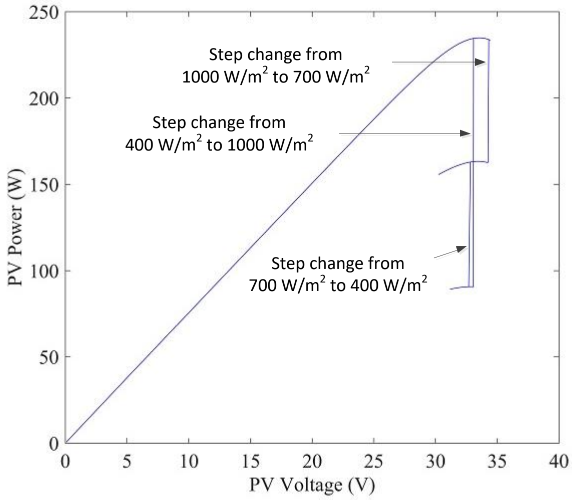


Fig. 9. P-V characteristics of PV panel for step changes in insolation

Power waveform shows the capability of the controller to track this gradual change in insolation. Fig. 6(b) shows the DC link voltage and current waveforms. Because of bipolar PWM, DC side current show the sinusoidal envelope on both positive and negative side. Fig. 6(c) shows AC side grid voltage and inverter current waveform. Because of feed forward mechanism, AC side current waveforms also demonstrate very good dynamics. Neglecting power loss, an average of AC instantaneous power is equal to PV average power.

For the second test also, initially, insolation and temperature are set at 1000W/m^2 and 25^{o}C respectively. Step fall in insolation from 1000W/m^2 to 700W/m^2 is applied at 0.2sec, followed by step fall in insolation from 700W/m^2 to 400W/m^2 at 0.3sec. Further step rise in insolation from 400W/m^2 to 1000W/m^2 is applied at 0.4sec. Fig. 7(a) presents the voltage, current and power waveforms of PV panel for applied step changes.

For a step change in insolation also, controller dynamic response is excellent. Also, there is a negligible overshoot in current waveforms. Fig. 7(b) presents the DC link voltage and current waveforms. Fig. 7(c) presents AC side grid voltage and inverter current waveform.

The plot of Power vs Voltage curve which demonstrates tracking of this controller for above applied the gradual change in insolation is shown in Fig. 8. The plot of Power vs Voltage curve which demonstrates tracking of this SM-like controller for an above-applied step change in insolation is shown in Fig. 9. In fact, the voltage at MPP for different insolation is almost constant. But this shift in tracking line is because of ripple on PV voltage waveform.

It is seen that the results of proposed SM-like controller for MPPT are better than other MPPT methods reported so far. This makes this controller suitable for PV applications where rapidly varying insolation condition exists. This proves the efficacy of the proposed controller.

6. Conclusion

In this paper, SM-like controller for MPPT of the grid-tied micro-inverter system with the front end quadratic converter is presented. The capability of proposed controller for fast MPPT under gradual and step variations in insolation, which results in improved efficiency of the overall system, is demonstrated through simulation. The simulation results show the robustness of the controller. The effectiveness of AC side feed forward controller for the grid-tied system is also well demonstrated. In addition to the fast tracking of MPPT, this controller exhibits minimum oscillations at MPP. The equivalent control ensures the fixed frequency operation of the controller which further confirms noise free operation. Selection of PV current for implementation of sliding line ensures use low bandwidth current sensor. The proposed controller can also be investigated for other buck/boost converters with proper selection of switching function.

References

[1] K. H. Hussein, I. Muta, T. Hoshino, and M. Osakada, “Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions”, *IEE Proceedings-Generation, Transmission and Distribution*, 142(1), pp.59-64, 1995. (Article)

[2] S. J. Chiang, K. T. Chang, and C. Y. Yen, “Residential photovoltaic energy storage system”, *IEEE Trans. on Ind. Electronics*, 45(3), pp. 385-394, 1998. (Article)

[3] S. Mehrnami, and S. Farhangi, “ Innovative decision reference based algorithm for photovoltaic maximum power point tracking” *Journal of Power Electronics*, 10(5), pp. 528-537, 2010. (Article)

[4] Y. Jiang, J. A. A. Qahouq, and T. A. Haskew, “Adaptive step size with adaptive-perturbation-

frequency digital MPPT controller for a single-sensor photovoltaic solar system", *IEEE Trans. on Power Electronics*, 28(7), pp. 3195-3205, 2013. (Article)

[5] L. V. Hartmann, M. A. Vitorino, M. B. de Rossiter Correa, and A. M. N. Lima, "Combining model-based and heuristic techniques for fast tracking the maximum-power point of photovoltaic systems", *IEEE Trans. on Power Electronics*, *28*(6), pp. 2875-2885, 2013. (Article)

[6] B. Veerasamy, A. R. Thelkar, G. Ramu, and T. Takeshita, "Efficient MPPT control for fast irradiation changes and partial shading conditions on PV systems", *In Renewable Energy Research and Applications (ICRERA), 2016 IEEE International Conference*, pp. 358-363, November 2016. (Conference Paper)

[7] T. Esram, and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques" *IEEE Trans. on Energy Conversion*, *22*(2), pp. 439-449, 2007.

[8] A. G. Sarigiannidis, S. A. Stathis, and A. G. Kladas, "Performance evaluation of MPPT techniques for PV array incorporated into Electric Vehicle roof", *In Renewable Energy Research and Applications (ICRERA), 2015 International Conference*, pp. 1069-1073, November 2015. (Conference Paper)

[9] X. Li, H. Wen, and Y. Hu, "Evaluation of different maximum power point tracking (MPPT) techniques based on practical meteorological data", *In Renewable Energy Research and Applications (ICRERA), 2016 IEEE International Conference*, pp. 696-701, November 2016. (Conference Paper)

[10] S. Öztürk, and I. Çaditoi, "A generalized and flexible control scheme for photovoltaic grid-tie microinverters. *In Renewable Energy Research and Applications (ICRERA), 2015 International Conference*, pp. 699-703, November 2015. (Conference Paper)

[11] D. Rekioua, T. Rekioua, and Y. Soufi, "Control of a grid connected photovoltaic system", In *Renewable Energy Research and Applications (ICRERA), 2015 International Conference*, pp. 1382-1387, November 2015. (Conference Paper)

[12] A. Dib, "Predictive Direct Power Control of a Grid Connected Three-Phase Voltage Source Inverter for Photovoltaic Systems", *International Journal of Renewable Energy Research (IJRER)*, *6*(1), pp.212-219, 2016. (Article)

[13] K. Arulkumar, D. Vijayakumar, and K. Palanisamy, "Recent advances and control techniques in grid connected PV system–A review", *International Journal of Renewable Energy Research (IJRER)*, *6*(3), pp.1037-1049, 2016. (Article)

[14] V. I. Utkin, J. Guldner, and J. Shi, *Sliding mode control in electromechanical systems*, CRC Press, 2nd. Edition, Taylor and Francis Group, USA, 2009. (Book)

[15] S. Kim, M. B. Kim, and M. J. Youn, "New maximum power point tracker using sliding-mode observer for estimation of solar array current in the grid-connected photovoltaic system", *IEEE Trans. on Ind. Electronics*, *53*(4), pp.1027-1035, 2006. (Article)

[16] C. C. Chu, and C. L. Chen, "Robust maximum power point tracking method for photovoltaic cells: A sliding mode control approach" *Solar Energy*, *83*(8), pp.1370-1378, 2009. (Article)

[17] L. Shang, D. Sun, and J. Hu, "Sliding-mode-based direct power control of grid-connected voltage-sourced inverters under unbalanced network conditions", *IET power electronics*, *4*(5), pp. 570-579, 2011. (Article)

[18] E. Bianconi, J. Calvente, R. Giral, E. Mamarelis, G. Petrone, C. A. Ramos-Paja, G. Spagnuolo and M. Vitelli, "A fast current-based MPPT technique employing sliding mode control", *IEEE Trans. on Industrial Electronics*, *60*(3), pp. 1168-1178, 2013. (Article)

[19] Y. Levron, and D. Shmilovitz, "Maximum power point tracking employing sliding mode control", *IEEE Trans. on Circuits and Systems I: Regular Papers*, *60*(3), pp.724-732, 2013. (Article)

[20] Z. Asma, D. Karim, and D. Tarak, "Maximum Power Point Tracking of Photovoltaic Systems Based on Fast Terminal Sliding Mode Controller" *International Journal of Renewable Energy Research (IJRER)*, *6*(4), pp.1435-1445, 2016. (Article)

[21] O. Lopez-Santos, G. García, and L. Martinez-Salamero, "Derivation of a global model of a two-stage photovoltaic microinverter using sliding-mode control", *In Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC), IEEE 13th Brazilian*, pp. 1-6, 2015. (Conference Paper)

[22] E. Mamarelis, G. Petrone, and G. Spagnuolo, "An hybrid digital-analog sliding mode controller for photovoltaic applications", *IEEE Trans. on Ind. Informatics*, *9*(2), pp.1094-1103, 2013. (Article)

[23] E. Mamarelis, G. Petrone, and G. Spagnuolo, "Design of a sliding-mode-controlled SEPIC for PV MPPT applications", *IEEE Trans. on Ind. Electronics*, *61*(7), pp. 3387-3398, 2014. (Article)

[24] R. Pradhan, and B. Subudhi, "Double integral sliding mode MPPT control of a photovoltaic system", *IEEE Trans. on Control Systems Technology*, *24*(1), pp. 285-292, 2016. (Article)

[25] N. Ghaffarzadeh, and S. Bijani, "Dual surface sliding mode controller for photovoltaic systems enhanced by a ripple domain search maximum power point tracking algorithm for fast changing environmental conditions", *IET Renewable Power Generation*, *10*(5), pp. 611-622, 2016. (Article)

[26] O. López-Santos, L. Martínez-Salamero, G. García, H. Valderrama-Blavi, and D. O. Mercuri, "Efficiency analysis of a sliding-mode controlled quadratic boost

converter", *IET Power Electronics*, 6(2), pp. 364-373, 2013. (Article)

[27] O. López-Santos, L. Martínez-Salamero, G. García, H. Valderrama-Blavi, and T. Sierra-Polanco, "Comparison of quadratic boost topologies operating under sliding-mode control", *In Power Electronics Conference (COBEP), 2013 Brazilian*, pp. 66-71, 2013. (Conference Paper)