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# Active power control of three-phase grid-connected solar PV systems using a robust nonlinear adaptive backstepping approach

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A B S T R A C T

This paper presents a robust controller design for three-phase grid-connected solar PhotoVoltaic (PV) systems to control active power. The controller is designed based on a nonlinear adaptive backstepping approach and the robustness of the proposed scheme is ensured by considering parametric uncertainties as well as external disturbances. In the proposed control strategy, all parameters within the grid-connected solar PV systems are considered as unknown which are then estimated through the adaptation laws. These estimated parameters along with external disturbances are incorporated into the controller to ensure the overall stability of the whole system through the formulation of Control Lyapunov Functions (CLFs). An Incremental Conductance (IC) method is used to track the Maximum Power Point (MPP) at which a constant DC-link voltage is maintained and this voltage is used to obtain the reference value of the current which is used for active power control. A three-phase grid-connected solar PV is used to evaluate the performance of the proposed control scheme under different operating conditions. The simulations results clearly indicate the robustness of the proposed scheme in terms of injecting active power into the grid and improving power quality as compared to an existing adaptive backstepping controller.



## 1. Introduction

The integration of solar PhotoVoltaic (PV) systems is increasing due to several advantages such as ease of installation, noiseless operation, safer operation with lower operational costs, and environment friendly operation without any air pollution (Vithayasrichareon and MacGill, 2016; Zakzouk et al., 2015; Tsang and Chan, 2013). Despite these advantages, there are several challenges for the grid integration of solar PV systems especially during the peak power generation (Yang et al., 2015). Moreover, the lifetime of solar PV generators are much less as compared to the conventional fossil fuel generators (Yang et al., 2015). Thus, it is essential to utilize the maximum benefit from solar PV systems which is possible if the maximum generated power can be delivered into the grid. This can only be achieved by controlling active power and operating the solar PV system at unity power factor (Hassaine et al., 2014; Bullich-Massaguá et al., 2017).

It is essential to track the Maximum Power Point (MPP) before delivering the maximum power into the grid through control action of the inverter. Maximum Power Point Tracking (MPPT) techniques are used to track the MPP of solar PV systems through DC–DC converters under changing atmospheric conditions (Subudhi and Pradhan, 2013; Zainuri1 et al., 2014; Elobaid et al., 2015; Faraji et al., 2014; Cecati et al., 2017). The Perturb and Observe (P&O) algorithm is the most commonly used one for extracting maximum power from PV arrays due to its simplicity (Bianconi et al., 2013; Ahmed and Salman, 2015). However, this method has several limitations, e.g., continuous oscillations around the operating point and poor tracking result or slower convergence speed. The Incremental Conductance (IC) method overcomes the limitations of the P&O method by providing faster convergence speed under changing atmospheric conditions (Sekhar and Mishra, 2014; Mei et al., 2011; Elgendy et al., 2016). After obtaining MPP, it is essential to control active power through switching actions of inverters.

Linear controllers are commonly used to control the active power in grid-connected solar PV systems (Selvaraj and Rahim, 2009; Dash and Kazerani, 2011; Rahim et al., 2007; Lauria and Coppola, 2014). These linear controllers are very useful to serve their purposes over a fixed set of operating points as these controllers are mainly designed based on linearized models of grid-connected solar PV systems. For this reason, linear controllers are

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unable to achieve desired control objectives under a wide variation of operating points, i.e., under rapidly changing of atmospheric conditions (Dash and Kazerani, 2011; Chowdhury, 2016).

Nonlinear controllers are used to overcome the limitation of operating points for grid-connected solar PV systems (Hao et al., 2013; Kotsopoulos et al., 2003; Mahmud et al., 2014; Mahmud et al., 2014; Lalili et al., 2011). There are different types of nonlinear controllers in the existing literature of grid-connected solar PV systems such as Sliding Mode Controller (SMC) (Hao et al., 2013), Model Predictive Controller (MPC) (Kotsopoulos et al., 2003), FeedBack Linearizing (FBL) controller (Mahmud et al., 2014; Mahmud et al., 2014; Lalili et al., 2011), and backstepping controller (Roy et al., 2015).

The FBL scheme is an effective way to control active power in grid-connected solar PV systems which cancels inherent nonlinearities using nonlinear coordinate transformation and transforms the nonlinear system into a fully or partially linearized one. An exact FBL scheme is used in Lalili et al. (2011), Zue and Chandra (2009) and Lalili et al. (2013) to control active power along with an aim to enhance dynamic stability. However, a grid-connected solar PV system may not always be exactly linearized and thus, this controller can be implemented by imposing unrealistic some assumptions on the dynamical model of the PV system. To overcome these problems, a partial FBL controller is proposed in Mahmud et al. (2014) and Mahmud et al. (2014) to control the active power over a wide range of operating regions. However, these FBL controllers are very sensitive to the variation of parameters within the grid-connected solar PV system. Moreover, the implementation of FBL controllers requires exact parametric values of the system which is really hard to know in practice. The MPC as proposed in Kotsopoulos et al. (2003) also provides similar benefits such as fast dynamic response, accurate reference tracking, and constant switching frequency. However, model predictive approaches are highly sensitive to the variations of systems parameters as well as external disturbances.

The SMCs provide robust performance against the parameter variations and external disturbances. A SMC is proposed in Kim (2006) and Kim (2007) to ensure the stability of a three-phase grid-connected PV system by controlling the current injection into the grid. Though this SMC has strong robustness and good regulation properties, the output power may significantly reduce due to chattering phenomenon. A similar control approach is proposed in Hu et al. (2011), Bakhshi and Sadeh (2016) and Yatimi and Aroudam (2016) which is mainly based on a time-varying sliding surface and the main aim is to control the power injection into the grid. However, the changes in atmospheric conditions are very fast in solar PV systems which make the selection of the time-varying sliding surface as extremely difficult.

Adaptive backstepping controllers provide promising solutions for maintaining the dynamic stability of three-phase grid-connected solar PV systems while considering the parameters of the system as completely unknown and dynamically estimating these parameters through the adaptation laws (Roy et al., 2016). A Lyapunov function based backstepping controller is proposed in Thao and Uchida (2013) to control power through the current injection into the grid. However, the backstepping controller does not consider neither parametric uncertainties nor external disturbances during the design process. An adaptive backstepping controller is used in Roy et al. (2016) where parametric uncertainties are considered and external disturbances are neglected. However, the external disturbances have significant effects on the stability of three-phase grid-connected solar PV systems and therefore, it is essential to design controller which has the capability to capture both external disturbances as well as parametric uncertainties.

This paper aims to control the active power injection into the grid from three-phase grid-connected solar PV systems through the regulation of the respective current using a robust adaptive backstepping technique. The proposed adaptive control scheme offers the following advantages as compared to the existing literature so far discussed in this paper:

- easy to integrate with the existing MPPT algorithm while ensuring better performance, e.g., the proposed scheme is used in conjunction with an existing IC-based MPPT method as discussed in Mei et al. (2011);
- parameter sensitivity problems of FBL techniques are overcome through the estimation of parameters;
- provides robustness against both parametric uncertainties and external disturbances while eliminating the necessity for the selection of the sliding surface;
- uses the estimated values of unknown parameters and considers the bound of external disturbances during the implementation of the proposed scheme and thus, ensures the tracking accuracy with minimum error (i.e., closed to 0%);
- injects power into the grid with improved power quality, i.e., with a lower value of Total Harmonic Distortion (THD) which is usually less than 2.5% though its standard value is around 5%; and
- allows to operate the system over a range of operating points with faster settling time.

In this paper, an IC-based MPPT technique is used to maintain a constant DC voltage across the DC-link capacitor which is later used to calculate the reference current. All parameters within the PV system are considered as unknown and estimated through the adaptation laws while the disturbances are bounded to ensure the overall stability of grid-connected PV systems. The overall stability is analyzed through the formulation of CLFs and the robustness of the proposed scheme against both parametric uncertainties and external disturbances is analyzed through simulation results under different operating conditions. All these actions are performed in such a way that the desired control objective is achieved, i.e., the desired active power is delivered into the grid with a lower value of the THD. The effectiveness of the proposed scheme is analyzed on a three-phase grid-connected solar PV system and compared with an existing adaptive backstepping approach (Roy et al., 2016).

## 2. Modeling of PV systems and control problem formulation

Fig. 1 shows a Voltage Source Inverter (VSI)-based three-phase grid-connected solar PV system. The system as shown in Fig. 1 comprises a PV array, DC-link capacitor ($C$), single-stage three-phase inverter with six switches ($S_1, S_2, S_3, S_4, S_5, \& S_6$), three connecting lines with resistor ($R$) as well as filter inductor ($L$), and grid supply point with three-phase voltages ($e_a, e_b$, and $e_c$). In this system, the MPP tracker is used to maintain a constant DC-link voltage and the proposed control scheme will ensure the convergence of this voltage to its desired value. In order to this, it is essential to

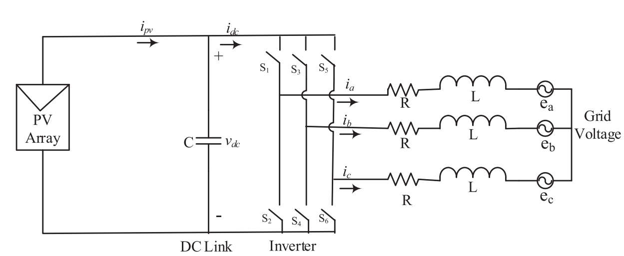


**Fig. 1.** Three-phase grid-connected PV system.