A Nonlinear Backstepping Controller of DC-DC Boost Converter for Maximizing Photovoltaic Power Extraction

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***Abstract*—The objective of this work is to integrate the backstepping control for tracking the maximum power point of a photovoltaic (PV) system. This control strategy is applied for a parallel DC-DC converter (type: boost) in order to regulate the output voltage of the PV generator, according to the reference voltage generated by the known Perturbation and Observation (P&O) MPPT (maximum power point tracking) algorithm. The nonlinear backstepping controller is based on Lyapunov function for ensuring the local stability of the system. The basic idea of the nonlinear backstepping controller is to synthesize a command law in a recursive way, that is to say step by step. This controller has a good transition response, a low tracking error, and a very fast response to the changes in solar irradiation and environmental temperature. To prove the effectiveness of the suggested control method, a comparative study through numerical simulations is presented with the classical PI (proportional-integral) controller.**

Keywords*— *Boost converter, backstepping control, maximum power point tracking (MPPT), photovoltaic chain.

I. Introduction

In recent years, a very important development of renewable energies has occurred . With its inexhaustible potential and no negative impact on the environment [1], renewable energy is an appropriate and accessible technology for economic growth and sustainable development [2]. The study of the renewable energy conversion chain: primary energy extraction, electrical conversion, power generation, network transformation, and integration, is a basic element to improve the quality of production of "green" energy.

Given the current interest of the world in renewable energy in general and solar energy especially, PV panels are used today in plenty of applications. The PV array has a single operating point that can supply maximum power to the load. This point is named the maximum power point (MPP). The locus of this point has a nonlinear variation with temperature and solar radiation. Thus in order work array at the MPP, the PV system must include a maximum power point tracking (MPPT controller)

The boost type DC-DC converter is used generally in the PV system as adaptation stage [3-4]. The boost converter is connected to the output of the PV array and controlled by MPPT (Maximumm power point tracking) algorithm in order to achieve the optimum voltage for harnessing the maximum PV energy.

Numerous MPPT methods have been developed and proposed in the literature such as P&O algorithm [5], sliding mode control (SMC) [6], fuzzy and artificial neural network methods [7-8] .

In this paper, a nonlinear backstepping controller, which modulates the duty cycle of a boost converter, is proposed. The output voltage of the solar array is the variable to be regulated; the output reference voltage of the PV is supplied by a P&O algorithm to obtain the MPP quickly, thus robustness is increased and Lyapunov's law ensures the global asymptotic stability and MPP is achieved even any environmental conditions.

This paper is organized as follows: in the second section description of PV chain, PV panel and boost converter modeling are introduced, in section III, the backstepping control is detailed. Section IV is devoted to analysis of the simulation results and comparison with PI controller and finally the conclusion .

II. Description of Photovoltaic Chain

The configuration of the PV chain under studied is given in **Fig. 1**. It represents a stand-alone structure composed of:

1. PV array which generates electric energy from solar energy.
2. DC-DC converter with resistive load controlled by backstepping controller to release the MPPT operation. The backstepping controller block is the most important part of the system because it guarantees the necessary energy to the load.

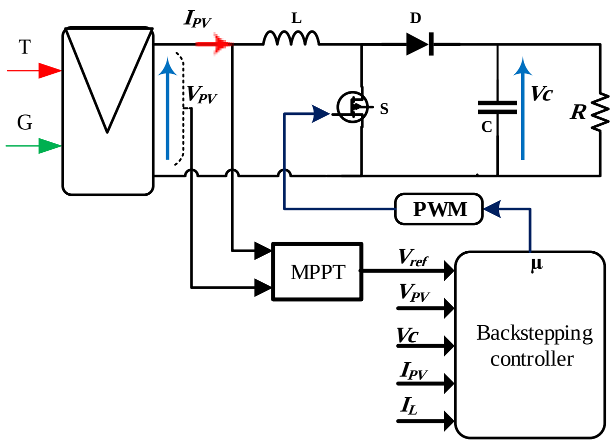

Fig. 1. Photovoltaic chain

A. PV Panel Modeling

The PV panel used in this study is SIEMENS SM 110-24, which is simulated using the model proposed in [9]. This model includes a current generator in parallel with single diode, and series parallel resistance. The current generated by the PV panel can be expressed by the following equations:

$$I_{PV} = I_{Ph} - I0\left[\exp\left(\frac{V_{PV} + Rs..I_{PV}}{\alpha.Vt}\right) - 1\right] - \left(\frac{V_{PV} + Rs.I_{PV}}{R_{Sh}}\right) \tag{1}$$

$$I_{Ph} = \left(I_{PV\_n} + Ki.\Delta T\right)\frac{G}{G_n} \tag{2}$$

$$Vt = \frac{Ns..K.T}{q} \tag{3}$$

$$I_0 = \frac{I_{sc\_n.} + K.\Delta T}{\exp\left(V_{oc\_n} + \frac{Kv.\Delta T}{\alpha.Vt}\right)} \tag{4}$$

Where:

$\Delta T = T - T_n$ (T and T_n are the actual and nominal temperature respectively).

I_{PV_n}, G_n, , T_n: are respectively the current generated by the light, irradiation and temperature under nominal conditions.

V_{PV}, I_{PV} : are the PV output voltage and current respectively.

Ki, Kv : are the current and voltage coefficients.

Voc_n, Isc_n : are respectively the open circuit voltage and short-circuit current of the panel at nominal temperature.

I_0 : dark saturation current.

I_{ph} : photo-generated current.

Vt : thermal voltage.

Rs And Rsh : Series and Shunt resistance respectively.

Ns: number of series cells in a PV panel.

α : diode quality factor.

q : electrical charge (q = 1,602. 10-19 Coulomb).

K : Boltzmann's constant (k = 1, 38. 10-23 J/K).

T : Ambient temperature.

T : Effective cell temperature (Kelvin).

The PV array consists of several PV panels connected in series and parallel. Therefore, depending on PV panel model given by the equation (3), the PV array model can be represented as:

$$I_{pv} = N_{pp}I_{ph} - N_{pp}I_0\left[\exp\left(\frac{Nss.Vpv + Rs.Ipv.\left(\frac{Nss}{Npp}\right)}{\alpha.Vt.Nss}\right) - 1\right] - \left(\frac{Nss.Vpv + Rs.Ipv.\left(\frac{Nss}{Npp}\right)}{Rsh\left(\frac{Nss}{Npp}\right)}\right) \tag{5}$$

Where *Nss*, *Npp* are the number of PV panels connected in series and parallel respectively.

B. Modeling of boost DC-DC Converter

The boost converter is used to step-up a DC voltage [3]. In the proposed technique, a boost converter is used. This converter is used to shift the PV array output voltage (*Vpv*) to the desired *Vmpp* by changing the duty cycle with the help of the backstepping controller. The principal circuit diagram of the boost converter is shown in **Fig. 2**. It consists of the following main components:

1. Input voltage from PV (V_{PV}).
2. Transistor switches (*S*).
3. Inductor (L).
4. Diodes (D_1 & D_2).
5. Capacitor (C_1 & C_2).
6. Load (R).

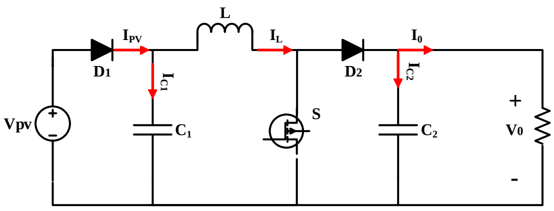

Fig. 2. Boost converter

It is assumed that the converter is operating in continuous conduction mode (the current I_L crossing the inductance never get zero). There are two operating intervals of the converter i.e. ***interval 1***, in which the switch is turned ***On***, and ***interval 2***, in which the switch is turned ***Off***.

- ***interval 1***, for the first period ***µTs***: the IGBT switch (S) are ***ON***, load is disconnected due to the closed path by switch (S). Inductor (L) is charged from PV through switch (S) in this mode.

Using kirchhoff's voltage and current law, we can write

$$\begin{cases} Ic_1 = C_1\dfrac{dV_{PV}}{dt} = I_{PV} - I_L \\ Ic_2 = C_2\dfrac{dV_0}{dt} = -I_0 \\ V_L = L\dfrac{dI_L}{dt} = V_{PV} \end{cases} \tag{6}$$

- ***Interval 2***, for the second period ***(1-µ) Ts***: the switch (S) are turned ***OFF*** and the load is connected to inductor (L) through diode (D_2).

Using kirchhoff's law, it yields

$$
\begin{cases} Ic_1 = C_1 \dfrac{dV_{PV}}{dt} = I_{PV} - I_L \\ Ic_2 = C_2 \dfrac{dV_0}{dt} = I_L - I_0 \\ V_L = L\dfrac{dI_L}{dt} = V_{PV} - V_0 \end{cases} \tag{7}
$$

To find a dynamic representation valid for all the period *Ts*, one generally uses the following averaging expression :

$$
\frac{dx}{dt}Ts = \frac{dx}{dt_{\mu Ts}}\mu Ts + \frac{dx}{dt_{(1-\mu)Ts}}(1-\mu)Ts \tag{8}
$$

Applying the relation (8) to the systems of equations (6) and (7), we get the average model of the boost converter :

$$
\begin{cases} \dfrac{dV_{PV}}{dt} = \dfrac{I_{PV}}{C_1} - \dfrac{I_L}{C_1} \\ \dfrac{dV_0}{dt} = (1-\mu)\dfrac{I_L}{C_2} - \dfrac{I_0}{C_2} \\ \dfrac{dI_L}{dt} = \dfrac{V_{PV}}{L} - (1-\mu)\dfrac{V_0}{L} \end{cases} \tag{9}
$$

$$
\begin{cases} \dot{x}_1 = \dfrac{I_{PV}}{C_1} - \dfrac{x_2}{C_1} \\ \dot{x}_2 = \dfrac{x_1}{L} - (1-\mu)\dfrac{V_0}{L} \end{cases} \tag{10}
$$

Where $x = [x_1\ x_2]^T = [V_{pv}\ \ I_L]^T$ represents the state vector and $\mu \in [0,1]$ is the duty cycles of the signal control.

III. BACKSTEPPING CONTROL

In order to extract the maximum power from the PV module, a nonlinear backstepping controller is designed to track the PV array output voltage ***Vpv* to *Vmpp*** by controlling the duty cycle of the converter. For this purpose,

- ***Step 1***

First of all, we define the error signal.

$$
e_1 = V_{PV} - V_{ref} \tag{11}
$$

Where ***Vref*** is the reference voltage generated by P&O algorithm. By converging the e_1 to zero, we can get the desired result.

Using the system (10), the tracking error derivative is written as follows:

$$
\dot{e}_1 = \frac{I_{PV}}{C_1} - \frac{1}{C_1}x_2 - \dot{V}_{ref} \tag{12}
$$

The following lyapunov function is considered:

$$
V_1 = \frac{1}{2}e_1^2 \tag{13}
$$

In order to assure the asymptotic stability, the Lyapunov function must be positive definite and radially unbounded and its derivative with respect to time must be negative definite [10]. Taking the time derivative of equation (13), we get

$$
\dot{V}_1 = e_1\dot{e}_1 \tag{14}
$$

$$
\dot{V}_1 = e_1\left(\frac{I_{PV}}{C_1} - \frac{1}{C_1}x_2 - \dot{V}_{ref}\right) \tag{15}
$$

From this equation for the derivative of Lyapunov function to be negative, it is necessary to

$$
\frac{I_{PV}}{C_1} - \frac{1}{C_1}x_2 - \dot{V}_{ref} = -Ke_1 \tag{16}
$$

From where

$$
x_2 = C_1\left(K_1e_1 - \dot{V}_{ref}\right) + I_{PV} \tag{17}
$$

Using the values of x_2 from equation (17), equation (15) becomes:

$$
\dot{V}_1 = e_1\left(\frac{I_{PV}}{C_1} - \frac{1}{C_1}\left[C_1\left(K_1e_1 - \dot{V}_{ref}\right) + I_{PV}\right] - \dot{V}_{ref}\right) \tag{18}
$$

$$
\dot{V}_1 = e_1\left(\frac{I_{PV}}{C_1} - K_1e_1 + \dot{V}_{ref} - \frac{I_{PV}}{C_1} - \dot{V}_{ref}\right) \tag{19}
$$

$$
\dot{V}_1 = -K_1e_1^2 \tag{20}
$$

Since the derivative of $\boldsymbol{V_1}$ to be definitively negative, the value of $\boldsymbol{K_1}$ must be defined positively, and equation (14) must be satisfied.

β is the stabilization function, acts as a reference current for x_2. then defined by:

$$
\beta = C_1\left(K_1e_1 - \dot{V}_{ref}\right) + I_{PV} \tag{21}
$$

Hence the asymptotic stability of the system (10) in origin

- ***Step 2***

The second error variable, which represents the difference between the state variable x_2 and its desired value β, is defined by:

$$
e_2 = x_2 - \beta \tag{22}
$$

Or

$$
x_2 = e_2 + \beta \tag{23}
$$

Differentiating equation. (23), equation (12) becomes

$$\dot{e}_1 = \frac{I_{PV}}{C_1} - \frac{1}{C_1}(e_2 + \beta) - \dot{V}_{ref} \tag{24}$$

$$\dot{e}_1 = \frac{I_{PV}}{C_1} - \frac{1}{C_1}\beta - \dot{V}_{ref} - \frac{1}{C_1}e_2 \tag{25}$$

$$\dot{e}_1 = -K_1 e_1 - \frac{1}{C_1}e_2 \tag{26}$$

The derivative of e_2 can define as follows

$$\dot{e}_2 = \dot{x}_2 - \dot{\beta} \tag{27}$$

Therefore

$$\dot{e}_2 = \frac{1}{L}x_1 - \frac{1}{L}(1-\mu)V_0 - \dot{\beta} \tag{28}$$

$$\dot{e}_2 = \frac{1}{L}\left(x_1 - (1-\mu)V_0\right) - \dot{\beta} \tag{29}$$

To insure the asymptotic stability of the system and the convergence of the errors e_1 and e_2 to zero, a composite Lyapunov function V_t is defined whose time derivative should be negative definite for all value of x_1 and x_2.

$$V_t = V_1 + \frac{1}{2}e_2^2 \tag{30}$$

The derivative of V_t is:

$$\dot{V}_t = \dot{V}_1 + e_2\dot{e}_2 \tag{31}$$

$$\dot{V}_t = e_1\left[-K_1 e_1 - \frac{1}{C_1}e_2\right] + e_2\left[\frac{1}{L}\left(V_{PV} - (1-\mu)V_0\right) - \dot{\beta}\right] \tag{32}$$

$$V_t = -K_1 e_1^2 + e_2\left[-\frac{1}{C_1}e_1 + \frac{1}{L}\left(V_{PV} - (1-\mu)V_0\right) - \dot{\beta}\right] \tag{33}$$

For the derivative of V_t negative it is necessary to

$$-\frac{1}{C_1}e_1 + \frac{1}{L}\left(V_{PV} - (1-\mu)V_0\right) - \dot{\beta} = -K_2 e_2 \tag{34}$$

$$\mu = 1 - \frac{1}{V_0}\left[V_{PV} - L\dot{\beta} - L\left(\frac{1}{C_1}e_1 - K_2 e_2\right)\right] \tag{35}$$

IV. SIMULATION RESULTS

In this section, numerical simulation of the PV chain shown in Fig. 1 is developed and implemented in MATLAB/ Simulink® enivrement. The PV array considered in this work consists of four identical PV modules shared into two parallel branches of two series connected modules. The parameters for the PV module and the boost converter are indicated in Table 1. The backstepping controller parameters are shown in Table 2.

Table 1 . Pv module and the boost converter parameters.

	Parameters	Value
PV module	Maximum power (P_{mpp}) Open circuit voltage (V_{oc}) Short circuit current (I_{sc}) Voltage at P_{Max} (V_{mpp}) Current at P_{Max} (I_{mpp}) Number of cells connected in series (Ns) Number of cells connected in parallel (Np)	120 W 42.1 V 3.87 A 33.7 V 3.56 A 72 1
Boost converter	Input capacitor C1 Output capacitor C2 Inductor L Load R	1100µF 1100µF 1mH 50Ω

Table 2. Backstepping controller parameters.

Parameters	Value
K1	3000
K2	69980

A. Test under varying irradiance

Under this test, temperature is set constant at T= 25 °C and irradiance is changed abruptly after every 1.5 second. The varying levels of irradiance is shown in **Fig. 3**. Initial irradiance is G=1000 W/m², then it is decreased to G=400 W/m² at 1.5 second and finally it is increased to G=600 W/m² at 2.5 second and G=800 W/m² at 3.5 second.

It can be observed in **Fig. 4**, for each irradiance level, that the proposed controller tracks successfully the reference voltage. The performance of the proposed controller is then confirmed.

Fig. 5 illustrated the obtained result of PV array with backstepping controller. It can be observed that the proposed controller has a very high performance at any level irradiation change , the controller performed well.

Fig. 6 shows the convergence of error signal e_1 to zero under the abrupt variation of irradiance at 1 .5 second, 2.5 second and 3.5 second.

B. Test under varying tempurature

In this case, irradiance is set constant at G=1000 W/m^2 while temperature is abruptly varied . Initial temperature is set at T= 5 °C, then it is stepped up to T=25 °C at 1.5 second and T=45 °C at 2.5 second and T=65 °C at 3.5 second.

Fig. 7 shows the varying levels of the temperature. From PV array curves, the performance of the proposed controller (backstepping) is again confirmed, and good tracking to ***Vref*** shown in Fig. 8.

Fig. 10 shows the convergence of the error signal e_1 to zero under the variation of temperature at [1.5 ; 2.5 ; 3.5] second.

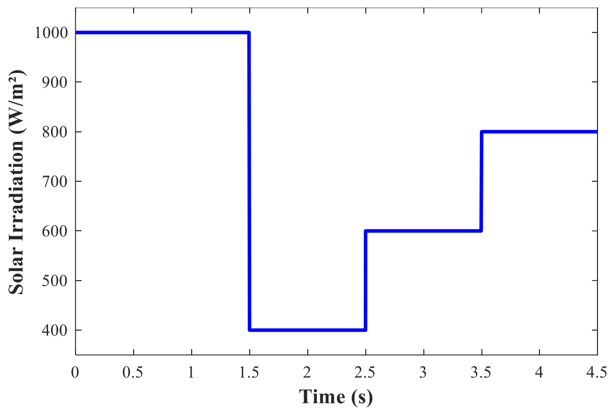

Fig. 3. Varying levels of irradiance.

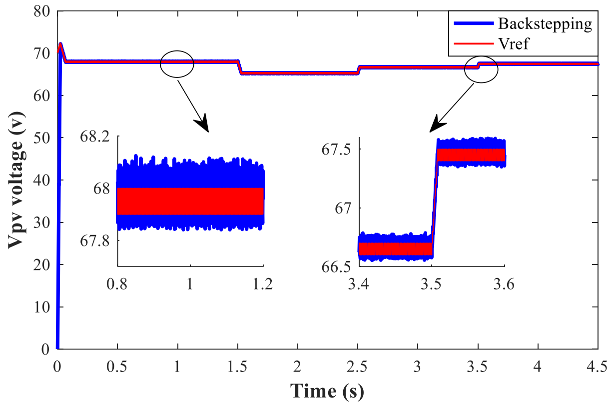

Fig. 4. Tracking of V_{PV} for different values of solar irradiation.

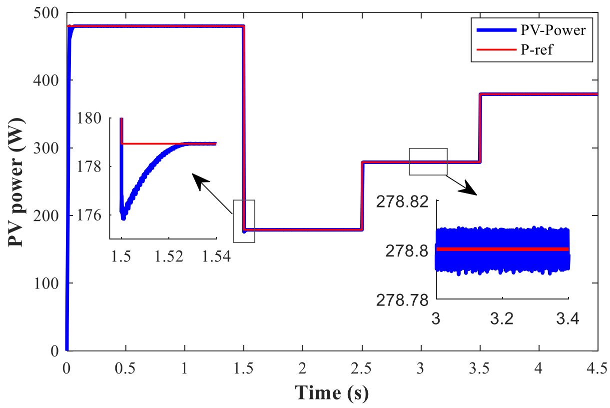

Fig. 5. Power of PV array for different values of solar irradiation.

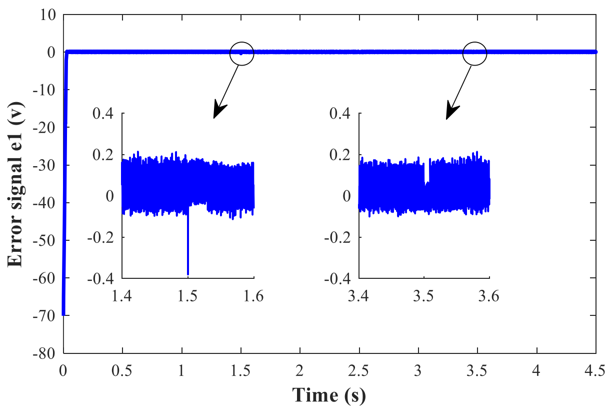

Fig. 6. error signal $\mathbf{e_1}$ under varying irradiance.

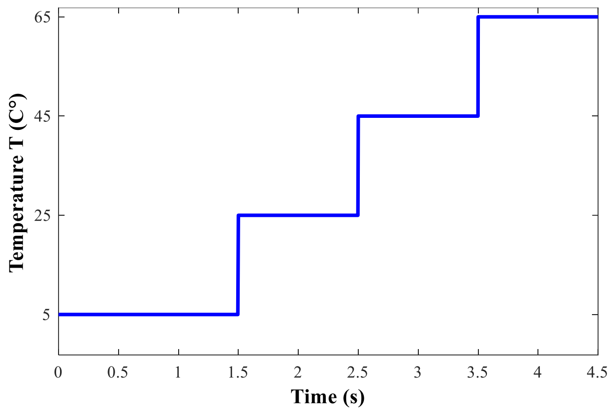

Fig. 7. Varying levels of temperature.

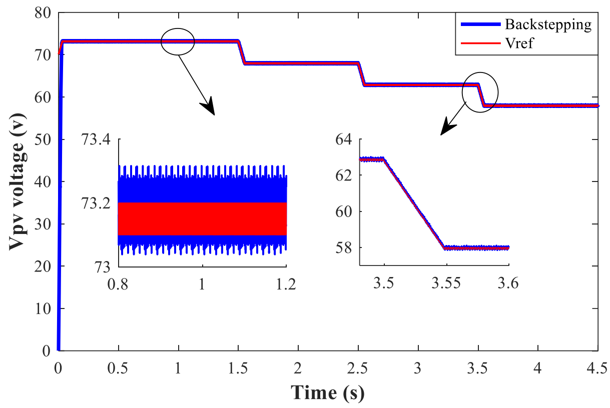

Fig. 8. Tracking of V_{PV} for different levels of temperature.

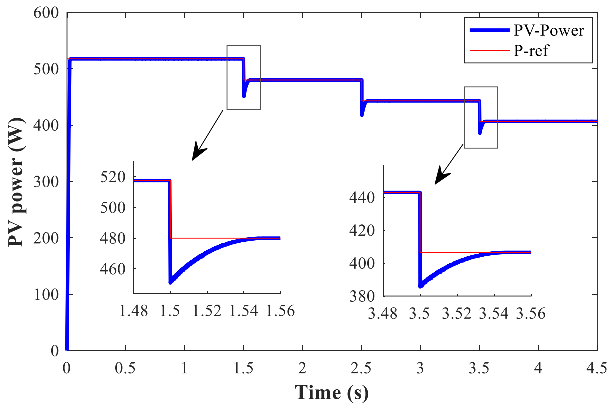

Fig. 9. Power of PV array for different levels of temperature.

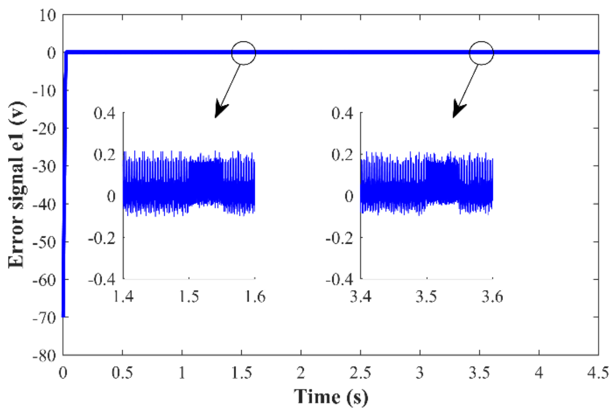

Fig. 10. error signal $\mathbf{e_1}$ under varying temperature.

V. COMPARISON WITH PI CONTROLLER

To show the performance of the backstepping controller, it is compared with (P&O/PI) controller. Both controllers are simulated and compared under varying temperature and irradiance levels.

A. Comparison under varying irradiance

In this comparison test, initially the irradiance is set at 1000 W/m² and is stepped down to 400 W/m² at 1.5 second , and set up to 600 W/m², 800 W/m² at 3 second.

Fig. 11 shows the Performance comparison of PI with the backstepping controller. It can be seen that not only the proposed controller reaches the MPP more rapidly than the PI, but during the variation of irradiance at [1.5; 2.5; 3.5]second, the backstepping controller is rapidly with minimal oscillations. To see the comparative behavior after the variation of irradiance at all times, **Fig. 11, Fig. 12** and **Fig. 13, Fig. 14** provides the zoomed view of ***PV power*** ***,current Ipv*** and ***Vpv voltage*** and ***error signal*** e_1 of the both controllers. It can be seen that the robustness of backstepping controller is valid for all changes of the irradiation levels.

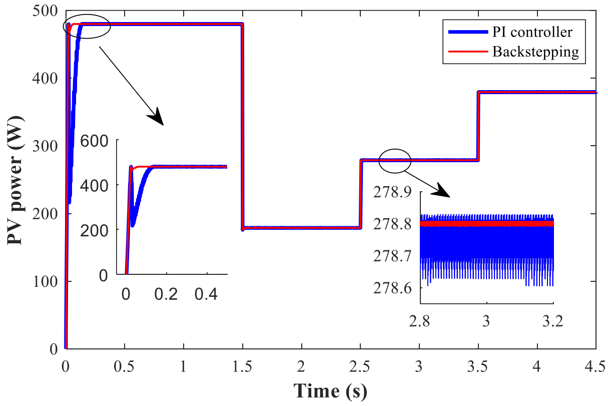

Fig 11. Backstepping vs PI power of PV array under variation irradiance.

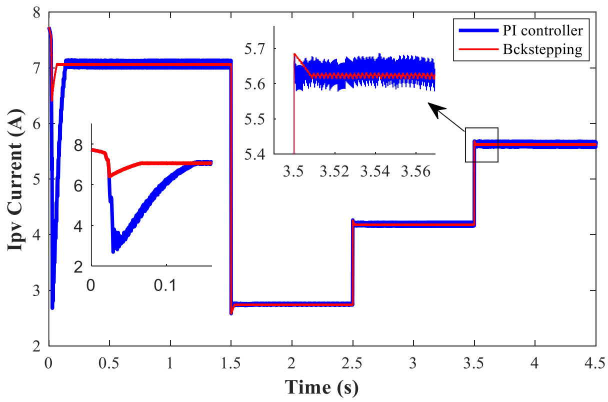

Fig 12. Backstepping vs PI tracking of I_{PV} current.

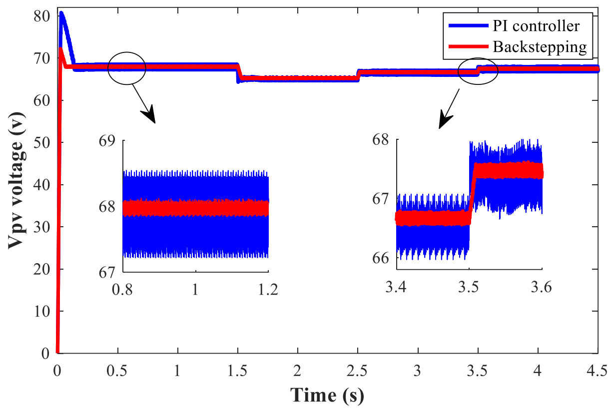

Fig. 13. Backstepping vs PI tracking of V_{PV}.

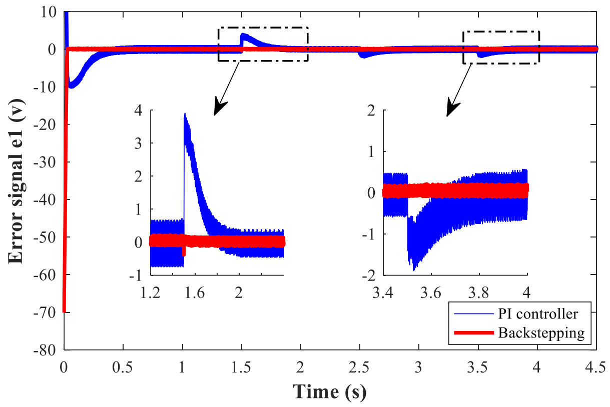

Fig. 14. Backstepping vs PI error signal $\mathbf{e_1}$ under varying irradiance.

B. Comparison under varying temperature

In the second comparison test, both controllers are tested done under varying temperature levels. The irradiance is set constant at 1000 W/m² and temperature is stepped up from T= 5 °C to T = 25 °C at 1.5 seconds, and T=45 °C at 2.5 seconds to 65 °C at 3.5 seconds.

In **Figs. 15 to 18**, it can be seen that the proposed controller reaches our system in a minimal time with fewer oscillations as compared to PI controller.

On the same figures a zoomed view of the oscillations around the MPP of the two controllers.

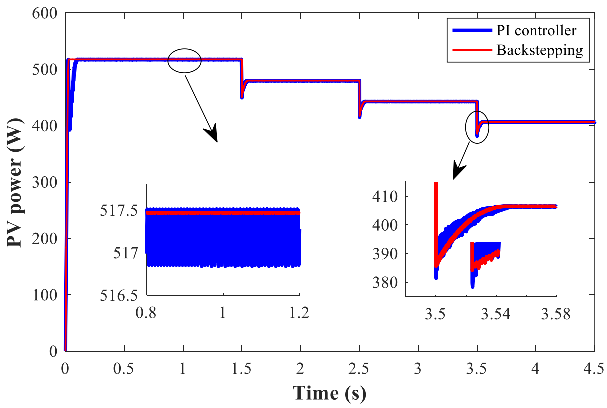

Fig. 15. Backstepping vs PI power of PV array under variation temperature.

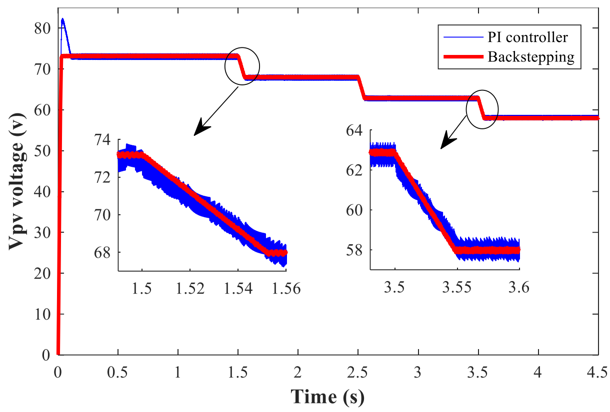

Fig. 16. Backstepping vs PI tracking of V_{PV}

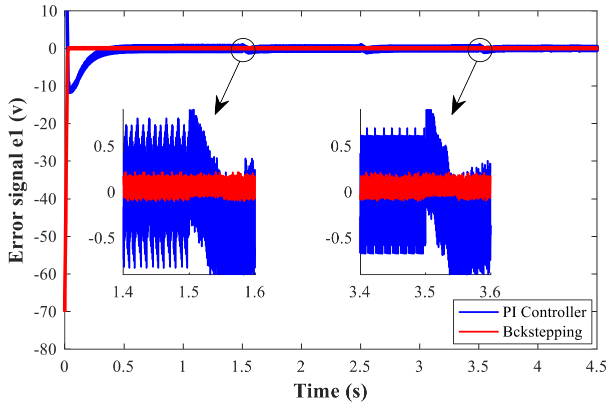

Fig. 17. Backstepping vs PI error signal **e_1** under varying irradiance

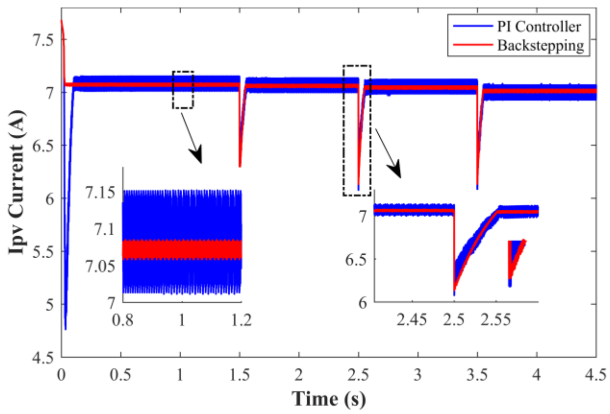

Fig. 18. Backstepping vs PI tracking of I_{PV} current

VI. Conclusions

In this paper, robust and nonlinear backstepping based controller has been employed to track the MPP of a PV system. The PV array is linked to the load through a boost converter. To get maximum power from PV array, duty cycle of the boost converter is controlled through which the PV array output voltage is tracked to the voltage reference generated by the P&O method .

The asymptotic stability of the system is verified via Lyapunov stability analysis. The simulation results show that the controller performed well under the sudden variation of environmental conditions, which prove the good robustness of the proposed controller.

The comparison with the P&O/PI controller is made which shows that the proposed controller performed better during the variation in the climatic conditions (irradiance and temperature levels). As a future perspective, an implementation of the proposed controller using a dSPACE system be introduced.

Acknowledgement

This paper is a part of the project PRFU: A10N01UN190120180002.

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