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Research Article

A New Sliding Mode Controller for DC/DC Converters in Photovoltaic Systems

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DC/DC converters are widely used in many industrial and electrical systems. As DC/DC converters are nonlinear and time-variant systems, the application of linear control techniques for the control of these converters is not suitable. In this paper, a new sliding mode controller is proposed as the indirect control method and compared to a simple direct control method in order to control a buck converter in photovoltaic applications. The solar arrays are dependent power sources with nonlinear voltage-current characteristics under different environmental conditions (insolation and temperature). From this point of view, the DC/DC converter is particularly suitable for the application of the sliding mode control in photovoltaic application, because of its controllable states. Simulations are performed in Matlab/Simulink software. The simulation results are presented for a step change in reference voltage and input voltage as well as step load variations. The simulations results of proposed method are compared with the conventional PID controller. The results show the good performance of the proposed sliding mode controller. The proposed method can be used for the other DC/DC converter.

1. Introduction

Modern electronic systems require high-quality, small, lightweight, reliable, and efficient power supplies. So, the DC/DC converters are widely used in many industrial and electrical systems. The most familiar are switching power supplies, DC drives, and photovoltaic systems. The stability is an important aspect in the design of switch mode power supplies; a feedback control is used to achieve the required performance. Ideally the circuit is in steady state, but actually the circuit is affected by line and load variations (disturbances), as well as variation of the circuit component (robustness). These parameters have a severe effect on the behavior of switch mode power supply and may cause instability. Design of controller for these converters is a major concern in power converters design [1–3].

Different control techniques are applied to regulate the DC-DC converters, especially buck converters, in order to obtain a robust output voltage [4, 5].

As DC/DC converters are nonlinear and time-variant systems, the application of linear control techniques for the control of these converters is not suitable. In order to design linear control system using classical linear control techniques, the small signal model is derived by the linearization around a precise operating point from the state space average model [4]. The controllers based on these techniques are simple to implement; however, it is difficult to account the variation of system parameters, because of the dependence of small signal model parameters on the converter operating point [6].

Sliding mode control is a well-known discontinuous feedback control technique which has been exhaustively explored in many books and journal articles. The technique is naturally suited for the regulation of switched controlled systems, such as power electronics devices, in general, and DC/DC power converters, in particular [2]. Many sliding mode controllers have been proposed and used for DC/DC converters [6–9]. These controllers are direct [6] or indirect control method [6, 7]. The direct method is proposed in [6]. In [7], the output capacitor current of DC/DC converter is used to control the output voltage. The differences of the DC/DC output voltage and the reference voltage enter the proportional-Integrator (PI) type controller, and then the output capacitor current of DC/DC converter is decreased from the output of controller [8]. The output voltage and inductor current are used to control of DC/DC converter in [9]. These references [6–9] have not completely investigated the load and line as well as reference regulations.

In this paper, a new sliding mode controller is introduced for DC/DC buck converter as the indirect control method. The proposed controller is compared with a simple direct control method as well as the conventional PID controller. The simulation results are presented for a step change in reference voltage and input voltage as well as for a step load variation. The main contribution of this paper is the presentation of a new indirect sliding mode controller with good accuracy and performance against load and line as well as reference regulations.

2. DC/DC Converters

The DC-DC converters can be divided into two main types: (1) hard-switching pulse width modulated (PWM) converters and (2) resonant and soft-switching converters [1].

Advantages of PWM converters include low component count, high efficiency, constant frequency operation, relatively simple control and commercial availability of integrated circuit controllers, and ability to achieve high conversion ratios for both step-down and step-up applications. The circuit diagram of the DC/DC buck converter is shown in Figure 1. In this figure, the circuit schematic is depicted with the transistor-diode symbols.

By sensing of the DC output and controlling of the switch duty cycle in a negative-feedback loop, the DC output voltage could be regulated against input line and output load changes [3].

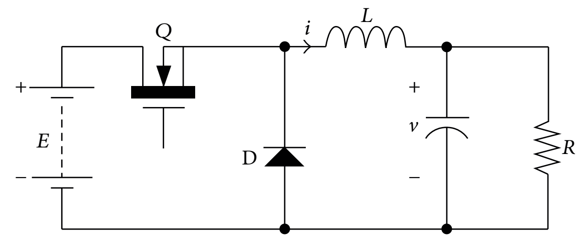

Figure 1: Semiconductor realization of the DC/DC buck converter.

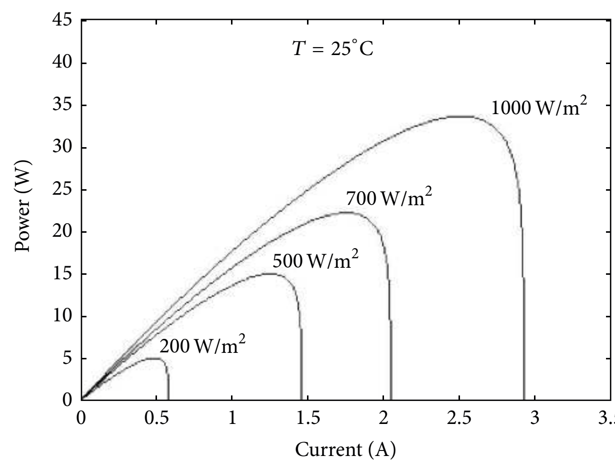

Figure 2: P-I characteristics of the solar array according to different insolation (for $T = 25^{\circ}$C).

3. Solar Array Characteristic

The solar arrays have nonlinear V-I characteristics which depend on the environmental conditions: ambient temperature and insolation.

The nonlinear characteristic of a solar sell is obtained as the following equation [10, 11]:

$$i_{SA} = I_{ph} - I_o \left\{ \exp\left(\left(\frac{q}{AKT} \right) \cdot \left(v_{SA} + R_S i_{SA} \right) \right) - 1 \right\}, \tag{1}$$

where I_{ph} is the generated current under a given insolation condition, I_o is the reverse saturation current, q is the charge of an electron, v_{SA} and i_{SA} are the output voltage and current of the solar cell, respectively, A is the ideality factor for a p-n junction, K is Boltzmann's constant, T is the temperature, and R_S is the series resistance of the solar cell. Figures 2 and 3 indicate the power-current (P-I) characteristic of a solar cell for different insolation and temperature, respectively.

4. The State-Space Model of Buck Converter

To obtain the differential equations describing the buck converter, the ideal topology is used as shown in Figure 4. The differential equations describing the DC/DC buck converter dynamics are obtained through the direct application of Kirchoff's current and Kirchoff's voltage laws for each one of the possible circuit topologies arising from the assumed particular switch position function value. Thus, when the switch position function exhibits the value $u = 1$, we obtain the topology corresponding to the nonconducting mode for the diode obtained. Alternatively, when the switch position exhibits the value $u = 0$, the second possible circuit topology corresponding to the conducting mode for the diode is obtained.

The system dynamics is described by the following differential equations.

For $u = 1$,

$$L\frac{di}{dt} = -v + E, \qquad C\frac{dv}{dt} = i - \frac{v}{R}. \tag{2}$$

For $u = 0$,

$$L\frac{di}{dt} = -v, \qquad C\frac{dv}{dt} = i - \frac{v}{R}. \tag{3}$$

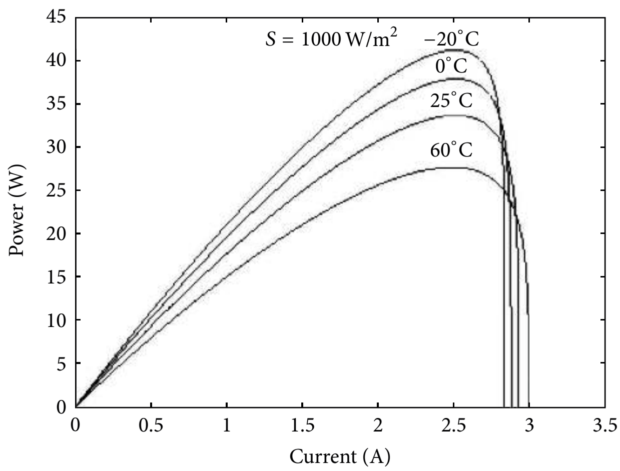

Figure 3: P-I characteristics of the solar array according to different temperature (for $S = 1000\ \mathrm{W/m^2}$).

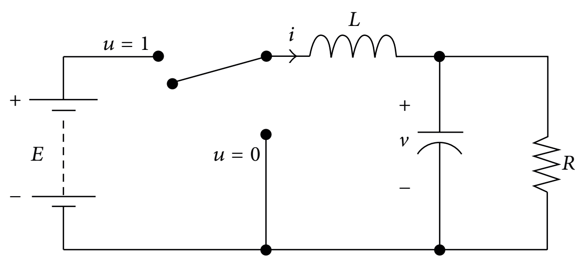

Figure 4: Ideal switch representation of the DC/DC buck converter.

By comparing the obtained particular dynamic systems descriptions, the following unified dynamic system model can be obtained:

$$L\frac{di}{dt} = -v + uE,$$
$$C\frac{dv}{dt} = i - \frac{v}{R}. \quad (4)$$

5. Sliding Mode Controller Design

In this section, two methods are presented in order to control the output voltage of a DC/DC buck converter. These methods are direct and indirect sliding mode control.

Direct control is based on the output voltage feedback, where the output voltage (V_C) is directly compared to the reference voltage (V_r).

Sliding surface is as follows:

$$S = V_C - V_r. \quad (5)$$

Indirect control is based on the inductor current control satisfying desired output voltage (V_r). In this method, because of the possible load variation, at first the output impedance (R_o) is determined by dividing the output voltage by the output current, and then the desired load current (I_{ld}) is calculated by dividing the reference voltage by the output impedance (R_o). By adding a coefficient of capacitor current (k) to I_{ld}, the desired inductor current (I_{lr}) is determined. So,

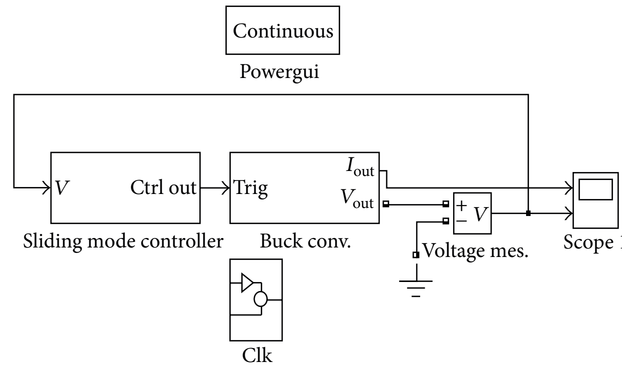

Figure 5: Simulink block diagram of direct sliding mode control.

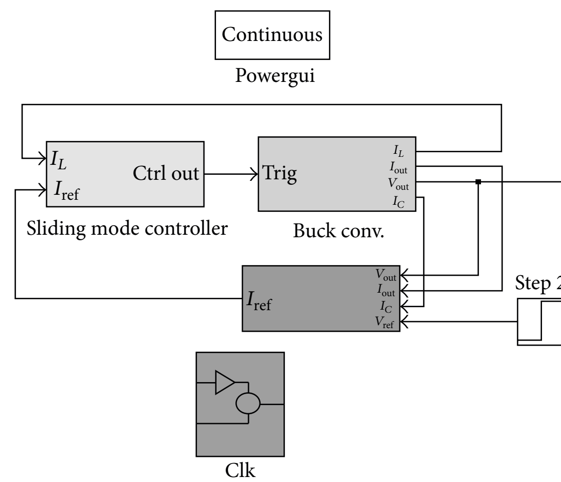

Figure 6: Simulink block diagram of indirect sliding mode control.

the sliding surface is defined by comparison between actual indirect current (I_l) and I_{lr} as the following.

Sliding surface can be computed as:

$$S = I_l - I_{lr}. \quad (6)$$

6. Simulation of DC/DC Converter with Sliding Mode Control

In order to investigate the proposed controller performance and accuracy, Matlab/Simulink and its facilities are used.

Simulations are performed on a typical buck converter with the following parameter values: $E = 10$ V, $L = 1$ mH, $C = 2200\ \mu$F, $R = 25$ W.

Figures 5 and 6 show the Simulink block diagram of direct and indirect sliding mode control of the proposed buck converter, respectively.

7. Results and Discussions

For the evaluation and validation of the proposed controller accuracy and performance, simulation results are presented in three subsections:

(a) analysis of the proposed sliding mode controller and determining the best sliding mode controller response;

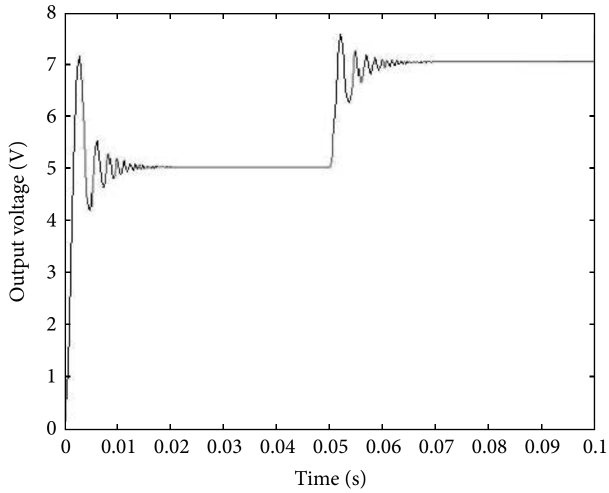

Figure 7: The DC/DC output voltage for a step change in reference voltage in direct control method.

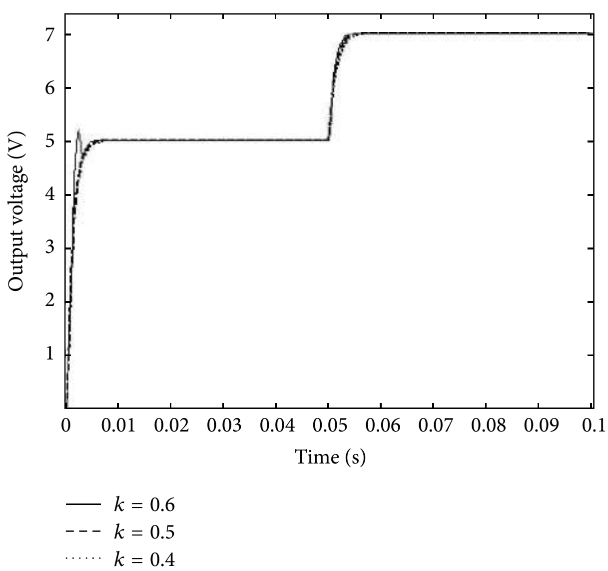

Figure 8: The DC/DC output voltage for a step change in reference voltage with respect to different values of k in indirect control method.

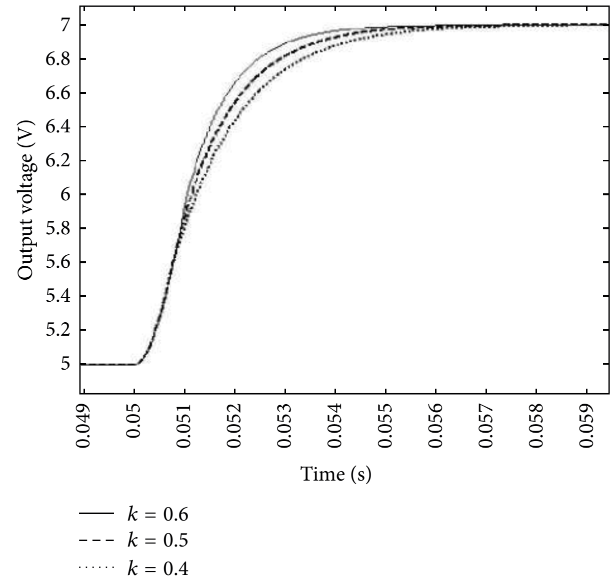

Figure 9: The DC/DC output voltage variation about reference variation time.

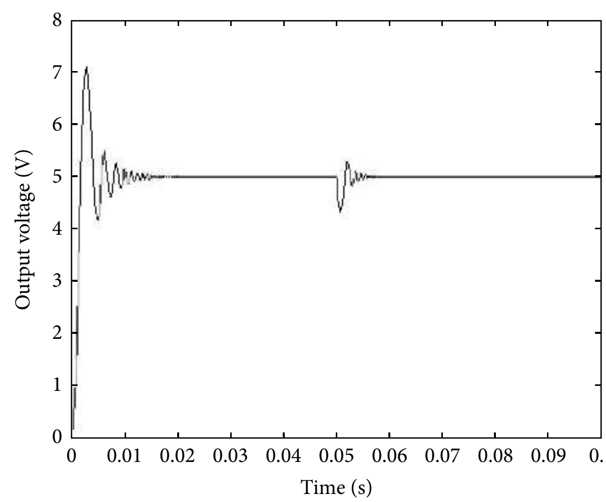

Figure 10: The DC/DC output voltage for step load variation in direct control method.

(b) comparison of the proposed sliding mode controller with the conventional PID controller;

(c) investigation of the proposed siding mode controller under environmental (insolation and temperature) conditions.

7.1. Simulation Results of the Proposed Sliding Mode Controller. Figures 7–9 show the output voltage during a change in reference voltage from $V = 5$ to $V = 7$ at $t = 0.05$ sec in direct and indirect control methods, respectively. Figure 7 shows the DC/DC output voltage for a step change in reference voltage (from $V = 5$ to $V = 7$ at $t = 0.05$ sec) in direct method. Figure 8 is plotted with respect to different values of k, where k is capacitor current coefficient.

Figure 9 indicates a zoom window about the output voltage variation.

In order to evaluate the robustness of sliding mode control, the load is changed from 1 Ω to 0.5 Ω at $t = 0.05$ sec. The results are indicated in Figures 10–12 for direct and indirect control methods, respectively. Figure 10 shows the DC/DC output voltage for a step change in load (from 1 Ω to 0.5 Ω at $t = 0.05$ sec) in direct method. Figure 11 is plotted with respect to different values of k. Figure 12 indicates a zoom window about the output voltage variation.

Figures 13–15 show the input voltage regulation, where the line voltage changes from $E = 10$ to $E = 20$ in $t = 0.05$ sec. Figure 13 shows the DC/DC output voltage for a step change in load (from 1 Ω to 0.5 Ω at $t = 0.05$ sec) in direct method. Figure 14 is plotted with respect to different values

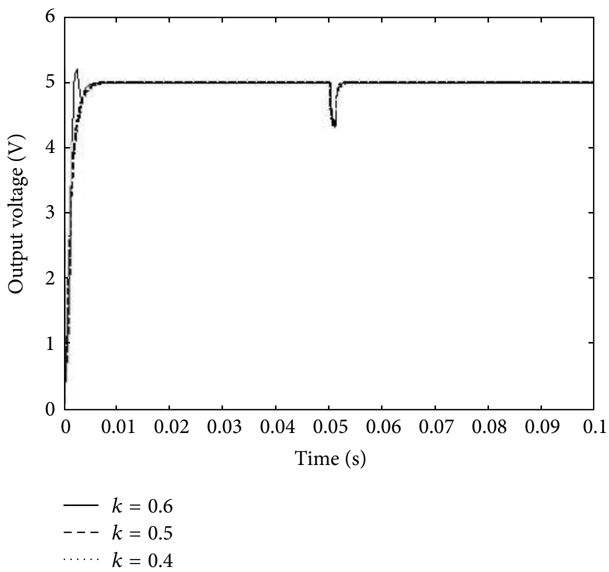

Figure 11: The DC/DC output voltage for step load variation with respect to different values of k in indirect control method.

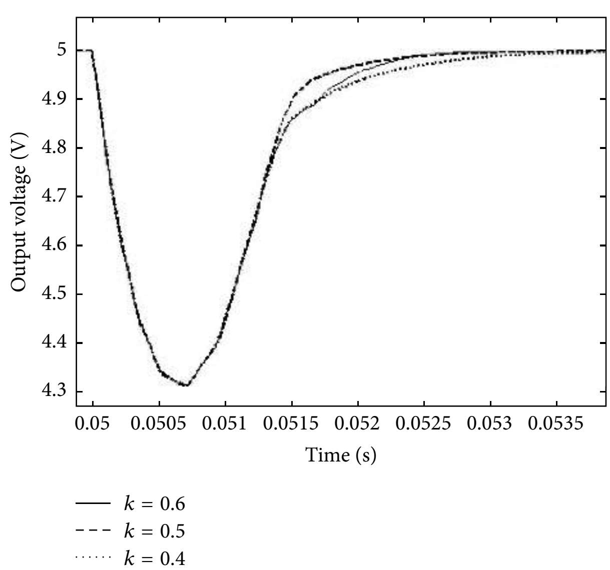

Figure 12: The DC/DC output voltage variation about step load variation time.

of k. Figure 15 indicates a zoom window about the output voltage variation.

These results (Figures 7–15) show that the direct control method does not have a good performance. On the other hand, indirect control performance is good but it is related to the k value. By the selection of suitable value of k, the indirect method performance is very good. The results show that the best performance is obtained for $k = 0.5$.

7.2. Comparison of Proposed Sliding Mode and PID Controller. For the validation of the proposed sliding mode controller, the best simulated result compares with conventional PID controller.

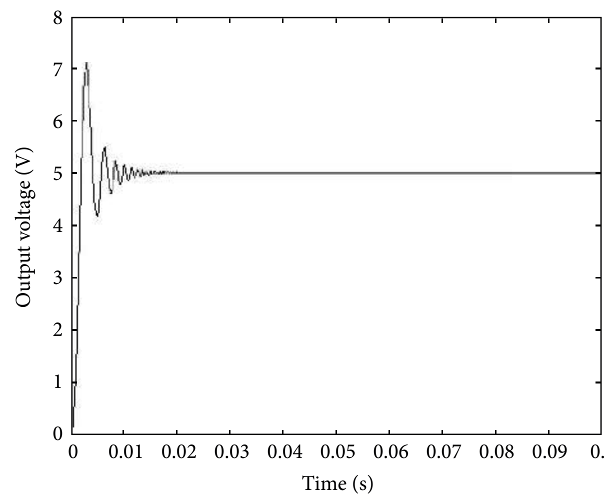

Figure 13: The DC/DC output voltage variation for a step change in line voltage in direct control method.

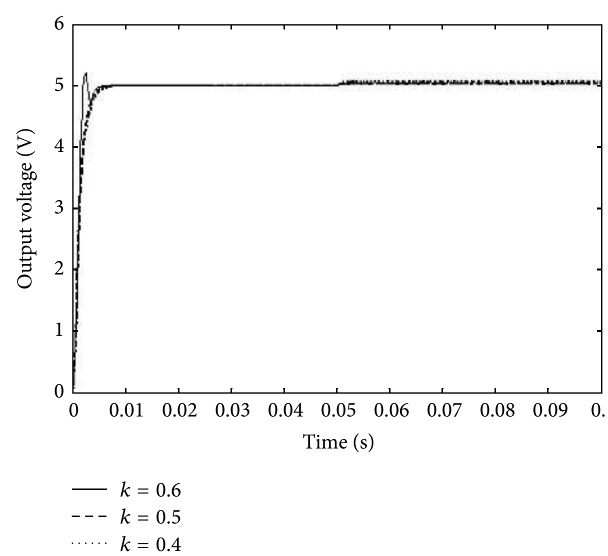

Figure 14: The DC/DC output voltage variation for a step change in Line voltage with respect to different values of k in indirect control method.

The best result is the one with the wave forms of indirect sliding mode control with capacitor current coefficient (k) equal to 0.5.

The noninteracting structure of PID controller is used. This is described by the following equation:

$$G_{\text{PID}} = k_P \left(1 + \frac{1}{sT_i} + sT_d \right), \quad (7)$$

where k_P is proportional gain and T_i, T_d are integrator and derivative time constants, respectively.

The simulation results of comparison between the proposed sliding mode controller and PID controller are indicated in Figures 16–19.

Figures 16 and 17 show the output voltage of buck converter with sliding mode and PID controller with a step

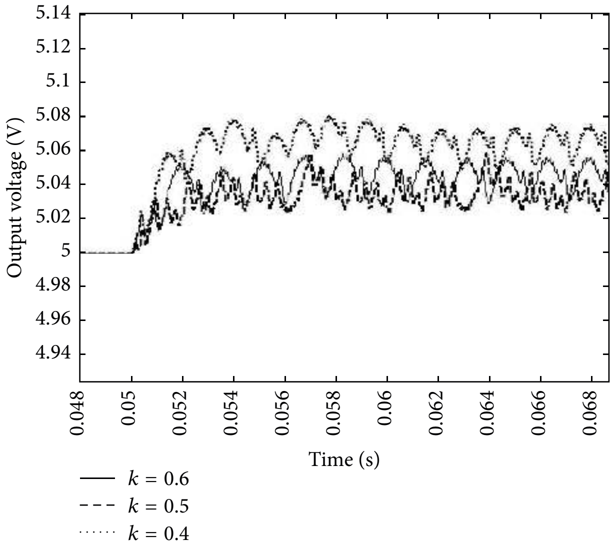

FIGURE 15: The DC/DC output voltage variation about line variation time.

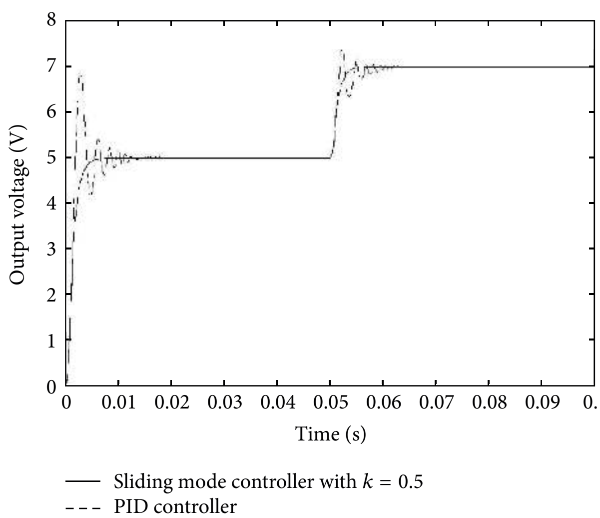

FIGURE 16: The DC/DC output voltage variation with a step change in reference voltage.

change in reference voltage from 5 V to 7 V at $t = 0.05$ sec. Figure 15 indicates a zoom window about the output voltage variation.

Finally, the load resistance is changed from 1 Ω to 0.5 Ω at $t = 0.05$ sec. The output voltage variation is indicated in Figure 18. Figure 19 shows a zoom window about the output voltage variation.

7.3. Investigation of the Proposed Sliding Mode Controller under Environmental (Insolation and Temperature) Conditions. In order to investigate of the accuracy of the proposed controller, a system includes a solar array, a DC/DC buck converter, and sliding mode controller. For testing the output voltage and current of photovoltaic array and then the output voltage of buck converter versus changing the environmental parameters instabilities, system was examined by changing

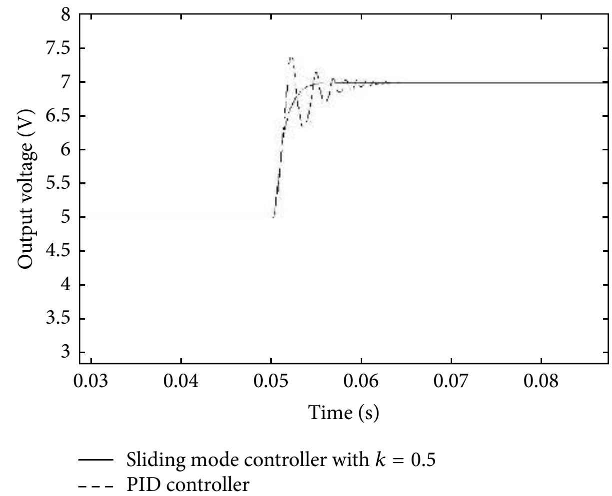

FIGURE 17: The DC/DC output voltage variation about reference voltage variation time.

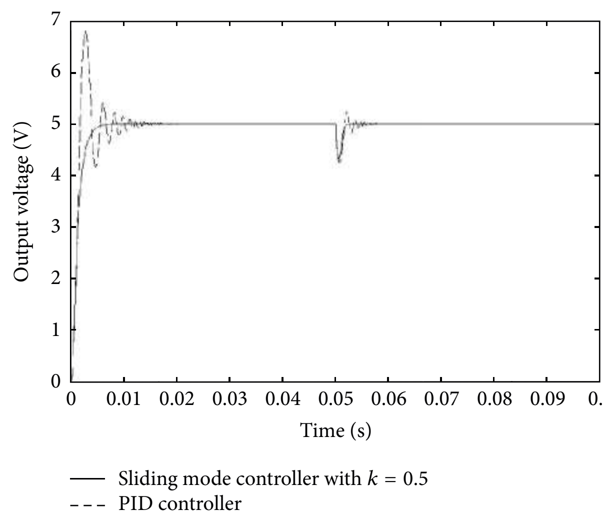

FIGURE 18: The DC/DC output voltage variation with a step change in load.

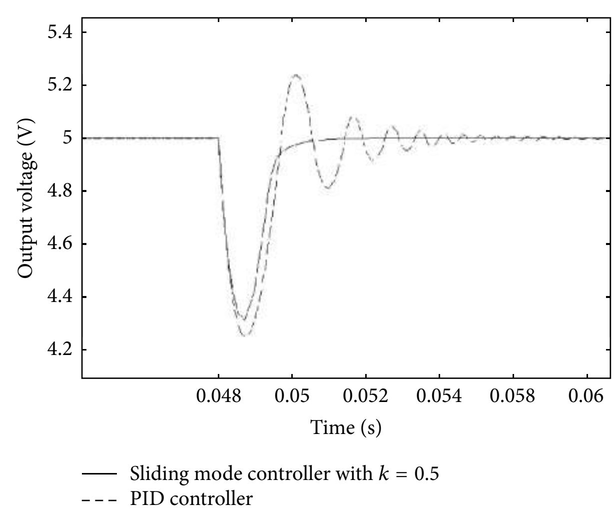

FIGURE 19: The DC/DC output voltage variation about load variation time.

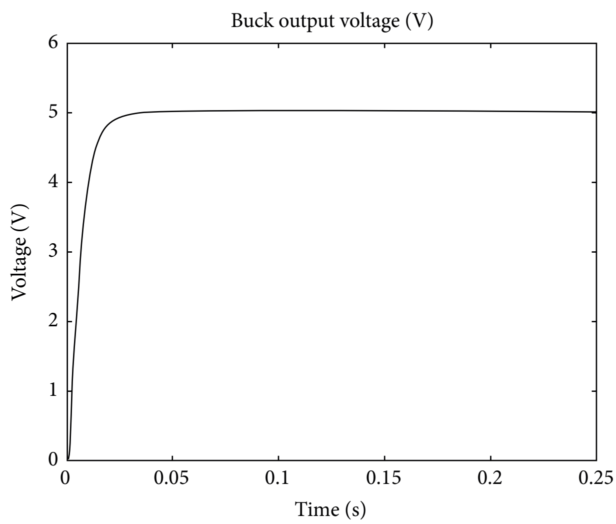

FIGURE 20: Output voltage of DC/DC converter for a step change in insolation from 900 (W/m^2) to 600 (W/m^2) in 30°C.

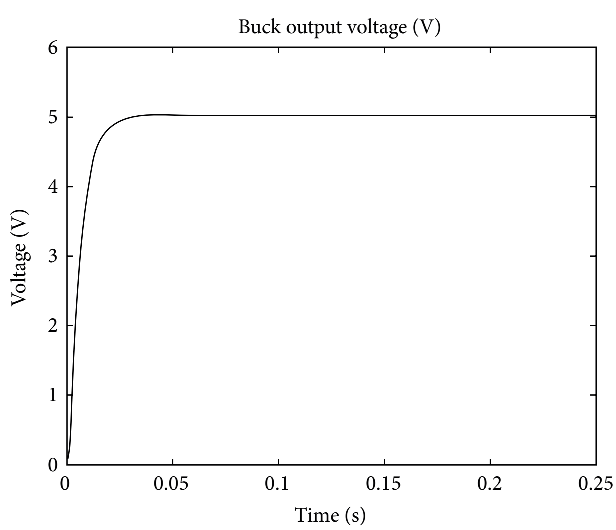

FIGURE 21: Output voltage of DC/DC converter for a step change in ambient temperature from 30°C to 20°C in constant insolation (900 (W/m^2)).

the insolation and ambient temperature of array. The results are illustrated in following figures.

In Figure 20, the insolation is changed from 900 (W/m^2) to 300 (W/m^2) in 30°C ambient temperature at $t = 0.025$ sec. As indicated in these figures, the voltage variation in the output voltage of buck converter is not visible.

In Figure 21, the results of a step change in ambient temperature from 30°C to 20°C in constant insolation (900 (W/m^2)) at $t = 0.025$ sec are illustrated.

8. Conclusion

In this paper, a new indirect sliding mode controller for DC/DC converters is presented. The results of analysis and simulation of proposed method are compared by direct sliding mode as well as conventional PID controller. The main conclusions are the following.

(i) The proposed indirect sliding mode controller has more good performance as compared with direct sliding mode as well as PID control.

(ii) The performance of the proposed sliding mode controller is related to suitable selection of its parameter (k).

(iii) The proposed controller is robust to load and line as well as reference variations.

(iv) The proposed controller can be used to all types of DC/DC converters.

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