Chapter

Feedback Linearization Control of Interleaved Boost Converter Fed by PV Array

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Abstract

One of the powerful methods of nonlinear control is the feedback linearization technique. This technique consists of input state and input-output linearization methods. In this chapter, the feedback linearization technique, including input state and input-output linearization methods, is described. Then, input-output linearization method is used for output voltage control of interleaved boost converter. Firstly, mathematical model of the interleaved boost converter is derived after that the method is applied. Besides, the interleaved boost converter is fed by a PV array under irradiation level and ambient temperature change. As a result of the simulation study, output voltage control of interleaved boost converter under reference voltage change is realized as desired.

Keywords: feedback linearization, interleaved, boost, PV

1. Introduction

In nature, most of the system is nonlinear. However, the analysis and design of a nonlinear controller require complex mathematical procedures. On the other hand, linear methods provide easy analysis and design of control systems. Nonetheless conducting the control of a wide range and with parameters changes, linear control and analysis methods are not so powerful, especially in the power electronics system. Power electronics systems have a highly nonlinear nature because of the switching states of the power switch. So, for designing the proper controller for such systems, the usage of nonlinear control methods is required.

In literature, [1–3] give the fundamental analysis, design, and methods of nonlinear systems. [4] applies nonlinear control methods to the basic power electronics converters. [5] describes the design analysis and operation of power electronics converters, including buck, boost, and buck-boost converters. Feedback linearization technique classified under nonlinear control is applied to fundamental power electronics converter, including boost converter in [6, 7], buck converter in [8], buck-boost converter in [9, 10]. [11, 12] present another nonlinear control method that is a sliding mode controller for boost converter, [13] buck converter, and [14] buck-boost converter. Furthermore, adaptive-based nonlinear controller is presented for boost converter [15], buck converter [16], and buck-boost converter [17]. Robust nonlinear controller is designed for buck in [18], boost in [19], and buck-boost converter in [20].

In this chapter, firstly feedback linearization technique, one of the most useful nonlinear methods, is described. Then, input-output linearization method classified under the feedback linearization technique is applied to the interleaved boost converter. Besides, as a power supply of interleaved boost converter, PV array is used with solar irradiation and ambient temperature changes. Furthermore, a nonlinear controller is designed to control the output voltage of the interleaved boost converter. After designing the nonlinear controller of interleaved boost converter, it is compared to a linear controller. As a result of the simulation study, it is concluded that a nonlinear controller for the output voltage of interleaved boost converter gives better results than a linear type controller.

2. Feedback linearization

Feedback linearization techniques have become very popular in recent years because of providing the linear equivalent systems of nonlinear systems by exact linearization. Feedback linearization techniques provides the transformations of nonlinear systems into fully or partly linear systems, algebraically so that linear control techniques can be used. In feedback linearization, linearization is realized by exact state transformation and feedback, making these techniques different from conventional linearization aiming linear approximation of the system.

Feedback linearization technique can be classified into two methods that are input-state linearization and input–output linearization.

2.1 Input-state linearization

In input-state linearization method, it is aimed to linearize state Eq. (1) completely. In order to cancel the nonlinearities in the original system, state transformation and input transformation are used. After applying the proper transformation, nonlinear system is transformed into the linear system [2].

If there is a nonlinear system given with the form of Eq. (1).

$$\dot{x} = f(x, u) \tag{1}$$

There should be a state transformation given in Eq. (2) and an input transformation in Eq. (3) in order to apply input-state linearization.

$$z = z(x) \tag{2}$$

$$u = u(x, v) \tag{3}$$

There are some points to bear in mind about applying input-state control, which are as follows:

- Even though the results obtained by input-state linearization control is valid in a large region, they may not be global. There may also occur some singularity points, while the initial state is at those points, controller may not bring the system to the equilibrium point.

- To apply control law, state transformation in Eq. (2) should be available. If state components are not physically meaningful or could not be measured, original states should be used to compute state components.

- If there is uncertainty in the model or in any parameters of the system, it causes an error in the calculation of new state **z** and control input **u**.

2.2 Input-output linearization

Another feedback linearization method is input-output linearization method. In this method, the main process is to generate a linear differential relation between the system output and new control input. This method can be summarized in three stages, as follows [1, 2]:

1. Differentiate the system output till control input appears,

2. Select new control input in order to guarantee tracking convergence and cancel nonlinearities,

3. Examine the stability of internal dynamics.

In order to explain input-output linearization method, think about a system given in Eqs. (4) and (5).

$$\dot{x} = f(x) + g(x)u \tag{4}$$

$$y = h(x) \tag{5}$$

To have input-output relation, output should be differentiated till input appears. After differentiating Eq. (5), Eq. (6) is acquired as in refs. [1, 2, 10].

$$\dot{y} = \frac{\partial h}{\partial x}[f(x) + g(x)u] = L_f h(x) + L_g h(x)u \tag{6}$$

$L_f h$ and $L_g h$ in Eq. (6) are described as Lie derivatives of f(x) and h(x) and given in Eq. (7).

$$L_f h(x) = \frac{\partial h}{\partial x} f(x),\ L_g h(x) = \frac{\partial h}{\partial x} g(x) \tag{7}$$

After r_j times derivation of the output, considering the condition in Eq. (8), Eq. (9) is acquired.

$$L_{gi} L_f^{r-1} h_i(x) \neq 0 \tag{8}$$

$$y_i^{r_i} = L_f^{r_i} h_i + \sum_{i}^{n} \left(L_{gi} L_f^{r_i - 1} h_i \right) u_i \tag{9}$$

If there is a multi-input, multi-output system, considering to apply Eq. (9) to all outputs, Eq. (10) is obtained.

$$\begin{bmatrix} y_1^{r_1} \\ \dots \\ \dots \\ y_n^{r_n} \end{bmatrix} = \begin{bmatrix} L_f^{r_1} h_1(x) \\ \dots \\ \dots \\ L_f^{r_n} h_n(x) \end{bmatrix} + \begin{bmatrix} L_{g1} L_f^{r_1 - 1} h_1 & \cdots & L_{gn} L_f^{r_n - 1} h_1 \\ \vdots & \ddots & \vdots \\ L_{g1} L_f^{r_n - 1} h_1 & \cdots & L_{gn} L_f^{r_n - 1} h_n \end{bmatrix} \begin{bmatrix} u_1 \\ \dots \\ \dots \\ u_n \end{bmatrix} = \alpha(x) + E(x)u \tag{10}$$

After selecting new control variable, input–output linearization is acquired as in Eq. (11).

$$\begin{bmatrix} u_1 \\ \dots \\ \dots \\ u_n \end{bmatrix} = -E^{-1} \begin{bmatrix} L_f^{r_1} h_1(x) \\ \dots \\ \dots \\ L_f^{r_n} h_n(x) \end{bmatrix} + E^{-1} \begin{bmatrix} v_1 \\ \dots \\ \dots \\ v_n \end{bmatrix} \tag{11}$$

The relation between system output y and new control input v is given in Eq. (12). In Eq. (12), k is constant to be chosen ensuring the stability of the system.

$$\begin{bmatrix} y_1^{r_1} \\ \dots \\ \dots \\ y_n^{r_n} \end{bmatrix} = \begin{bmatrix} v_1 \\ \dots \\ \dots \\ v_n \end{bmatrix}, \begin{bmatrix} v_1 \\ \dots \\ \dots \\ v_n \end{bmatrix} = \begin{bmatrix} -k_{1(r-1)} y^{r-1} \dots - k_{11(r-1)} y^1 - k_{10}\left(y_1 - y_1^*\right) \\ \dots \\ \dots \\ -k_{n(r-1)} y^{r-1} \dots - k_{21(r-1)} y^1 \quad - k_{20}\left(y_n - y_n^*\right) \end{bmatrix} \tag{12}$$

Also Eq. (13) gives the closed loop error dynamics relating to system output, reference values, and k constants as in Ref. [21].

$$\begin{bmatrix} e \\ \dots \\ \dots \\ e^r \end{bmatrix} = \begin{bmatrix} y - y^* \\ \dots \\ y^r - y^{*\,r} \end{bmatrix}, \begin{bmatrix} e_1^r + k_{1(r-2)} e_1^{r-1} + \dots + k_{11} e_1^1 + k_{10} e_1 \\ \dots \\ e_n^r + k_{n(r-1} e_n^{r-1} + \dots + k_{21} e_n^1 + k_{20} e_n \end{bmatrix} = \begin{bmatrix} 0 \\ \dots \\ \dots \\ 0 \end{bmatrix} \tag{13}$$

2.3 Interleaved boost DC-DC converter

Circuit structure of interleaved boost DC-DC converter is shown in **Figure 1**. It is seen that two separate boost converters are connected to the DC bus. The difference of interleaved boost converter from boost converter is that both switches are conducted with time delay in order to have input current having less ripple content.

Operation of the interleaved boost converters can be summarized as follows: When S_1 is in switch-on position, S_2 is turned off, L_1 current increases linearly, L_2 current decreases, and D_2 conducts. When S_1 is switched off, S_2 is switched on and L_2 current increases linearly, L_1 current decreases, and D_1 conducts. While the inductor's current decreases, inductors transfer their energy to the load. Passive components of the interleaved boost converter can be chosen by using Eqs. (14) and (15) as in Ref. [5].

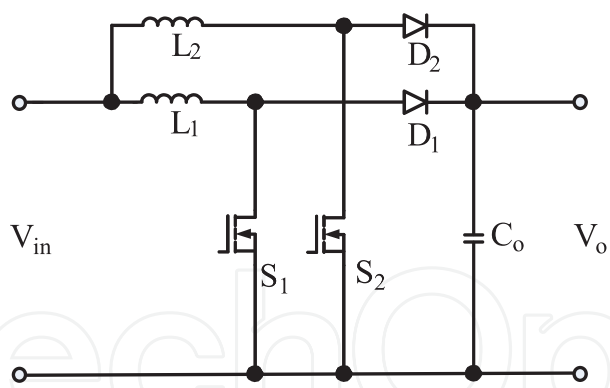

Figure 1.
Interleaved boost DC-DC converter.

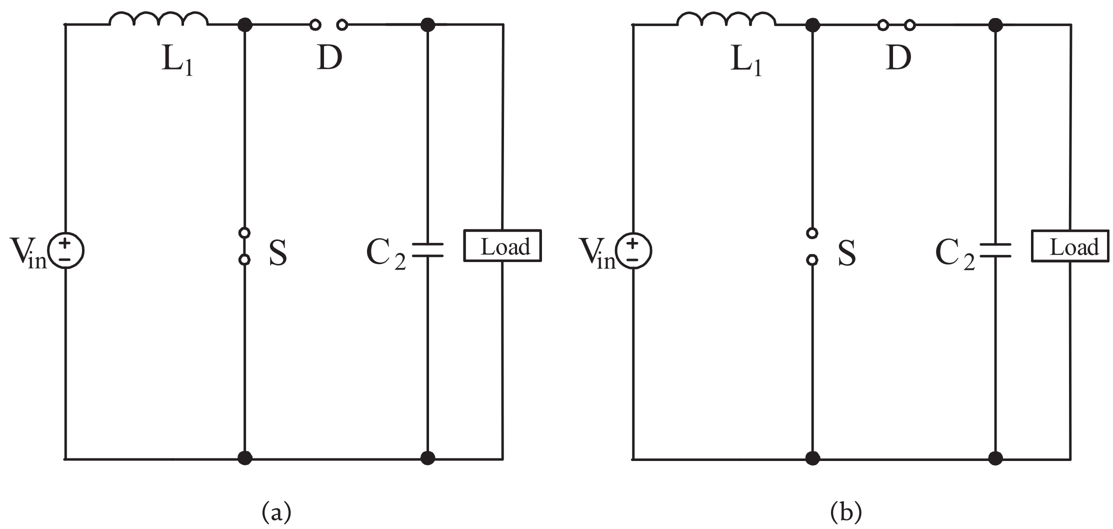

Figure 2.
(a) Switch-on, (b) switch-off position of the boost converter.

$$L = \frac{RD(1-D)^2}{2f_s} \tag{14}$$

$$C = \frac{DV_o}{f_s R \Delta V_C} \tag{15}$$

While deriving a mathematical model of interleaved boost DC-DC converter, model of boost DC-DC converter can be used. A mathematical model of the boost converter is obtained by switching on and off positions, shown in **Figure 2**. By applying Kirchhoff voltage and current laws for both circuits, a mathematical model of the boost converter is written.

At switch-on interval, after applying Kirchhoff voltage and current law, Eqs. (16) and (17) are obtained. The model for switch-on interval can be written in Eq. (19) with the form Eq. (18) of state-space representation.

$$\frac{di_L}{dt} = \frac{V_{in}}{L_1} \tag{16}$$

$$\frac{dV_o}{dt} = -\frac{V_o}{RC} \tag{17}$$

$$\dot{x} = Ax + Bu \tag{18}$$

$$\begin{bmatrix} \dot{i_L} \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -1/_{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_o \end{bmatrix} + \begin{bmatrix} 1/_L \\ 0 \end{bmatrix} V_{in} \tag{19}$$

At the switch-off interval, Kirchhoff voltage and current law are applied to **Figure 2b** and Eqs. (20) and (21) are obtained. It is also written in the form of Eq. (22).

$$\frac{di_L}{dt} = \frac{V_{in}}{L_1} - \frac{V_o}{L_1} \tag{20}$$

$$\frac{dV_o}{dt} = -\frac{i_L}{C} - \frac{V_o}{RC} \tag{21}$$

$$\begin{bmatrix} \dot{i_L} \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & -1/_L \\ 1/_C & -1/_{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_o \end{bmatrix} + \begin{bmatrix} 1/_L \\ 0 \end{bmatrix} V_{in} \tag{22}$$

Mathematical model of the boost converter can be derived in Eq. (24) by using state-space average technique given in Eq. (23).

$$A = dA_1 + (1-d)A_2,\ B = dB_1 + (1-d)B_2 \tag{23}$$

$$\begin{bmatrix} \dot{i_L} \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & ^{-1+d}/_L \\ ^{1-d}/_C & -1/_{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_o \end{bmatrix} + \begin{bmatrix} 1/_L \\ 0 \end{bmatrix} V_{in} \tag{24}$$

State-space mathematical mode in Eq. (24) can be reordered as in Eq. (25) to apply input–output linearization technique. As a system input in Eq. (25), d is chosen.

$$\begin{bmatrix} \dot{i_L} \\ V_o \end{bmatrix} = \begin{bmatrix} ^{V_o}/_L + ^{V_{in}}/_L \\ ^{i_L}/_C - ^{V_o}/_{RC} \end{bmatrix} + \begin{bmatrix} ^{V_o}/_L \\ ^{-i_L}/_C \end{bmatrix} d \tag{25}$$

The purpose of the control is to regulate output voltage V_o, so as an output variable V_o is chosen as in Eq. (26).

$$y = h(x) = V_o \tag{26}$$

The way of using input–output linearization techniques is to derive system output until system input is obtained in output. So, after derivation of system output V_o, Eq. (27) is obtained.

$$\dot{y} = \dot{V}_o = ^{i_L}/_C - ^{V_o}/_{RC} {}^{-i_L d}/_C \tag{27}$$

It is observed in (27) that at the first derivation, system input is found at system output. It means that the relative degree of the system is "1." Eq. (27) is rearranged in Eq. (28) with respect to system input.

$$d = \left(-\dot{V}_o + ^{i_L}/_C - ^{V_o}/_{RC}\right)\frac{C}{i_L} \tag{28}$$

The next stage is to choose a new control input. The control input is chosen regarding to relative degree in Eq. (29).

$$y^1 = V_1 \tag{29}$$

After choosing new control input as in Eq. (30), and replacing it in Eq. (28), Eq. (31) is obtained. Eq. (31) is the system input, nonlinear controller is operated with respect to it.

$$V_1 = k_1(V_o - V_o^*) \tag{30}$$

$$d = \left(-k_1(V_o - V_o^*) + {}^{i_L}\!/_{C} - {}^{V_o}\!/_{RC}\right)\frac{C}{i_L} \tag{31}$$

In order to provide the operation of the interleaved boost converter, S_1 is switched by using the duty cycle calculated in Eq. (31), and S_2 is switched by using the same duty cycle having 90° delay.

3. Simulations

Interleaved boost DC-DC converter fed by PV array is controlled by input–output linearization technique by means of the simulation. Simulation study is realized by Matlab/Simulink software. The circuit diagram of the study is shown in **Figure 3**. It is seen in the figure that there is a nonlinear controller that is based on the Eq. (31) in chapter 2.

It is seen that interleaved boost converter is connected to the output of the PV array. Because of the interleaved nature of the converter, input current has a lower

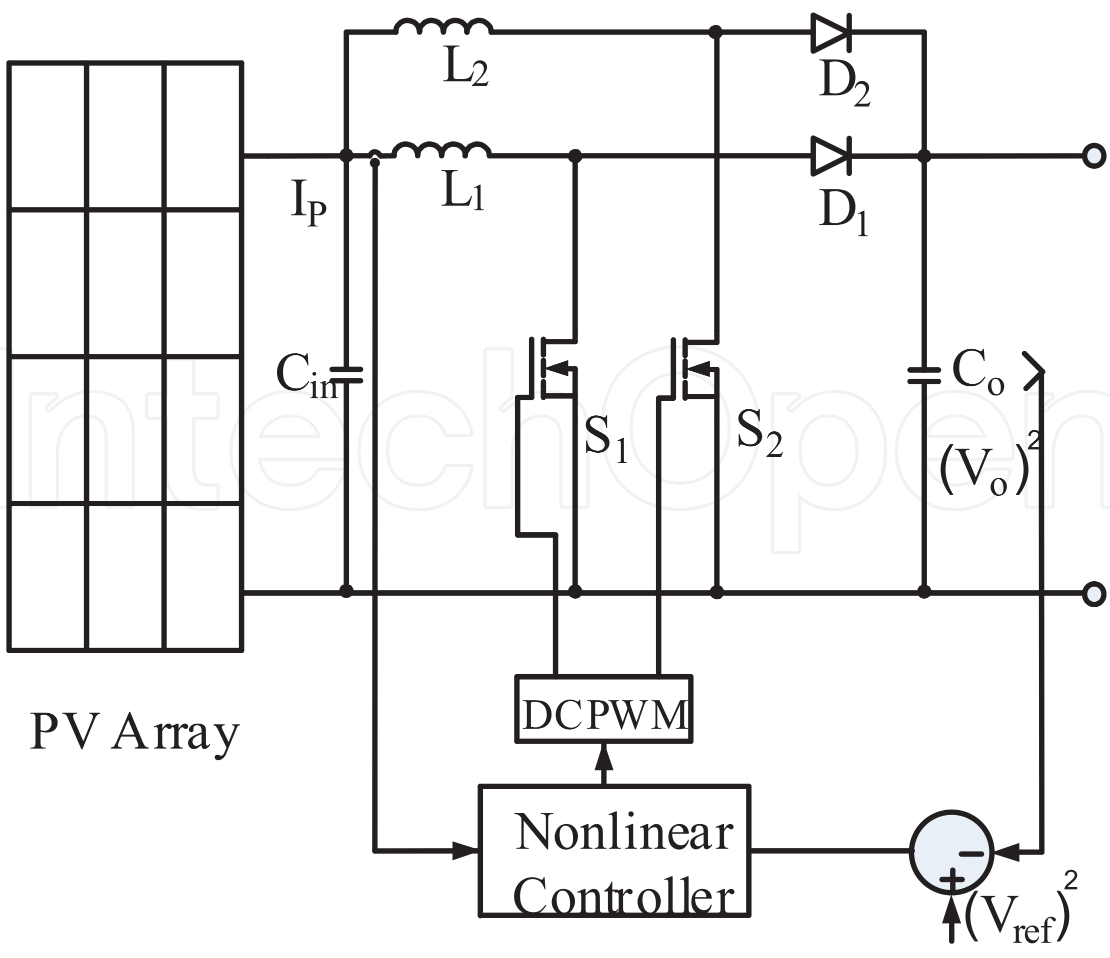

Figure 3.
PV-fed interleaved boost DC-DC converter with nonlinear control.

ripple than the classical boost converter. The simulation diagram of the circuit is shown in **Figure 4**.

Parameters used in the simulation are given in **Table 1**.

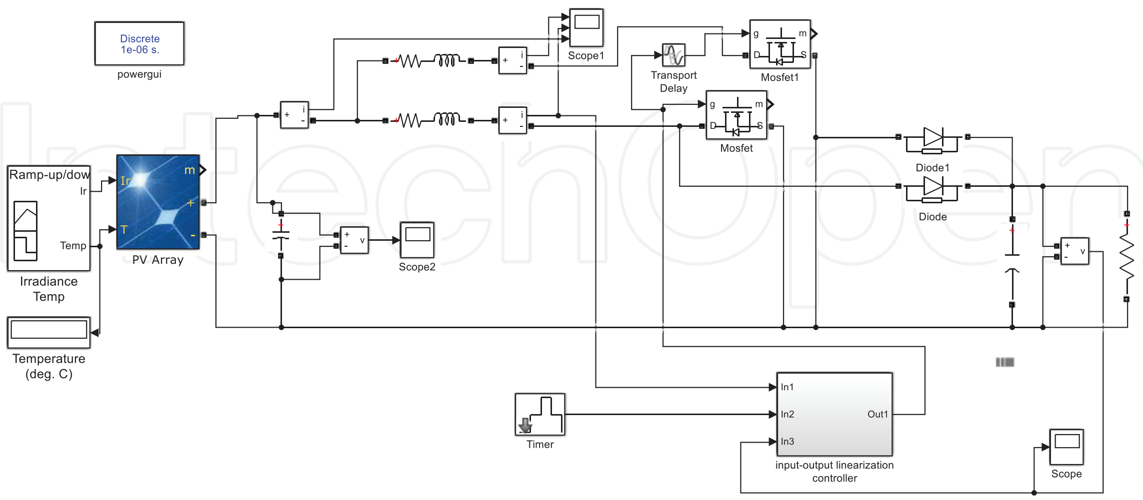

Figure 4.
PV-fed interleaved boost DC-DC converter simulation diagram.

L1, L2	C	R	f_{sw}	PV Array	PV Array
600 μH	1000 μH	250 Ω	69 kHz	40 prl, 2 srs	305 W Pmax, 64.2 Voc

Table 1.
Parameter values used in the study.

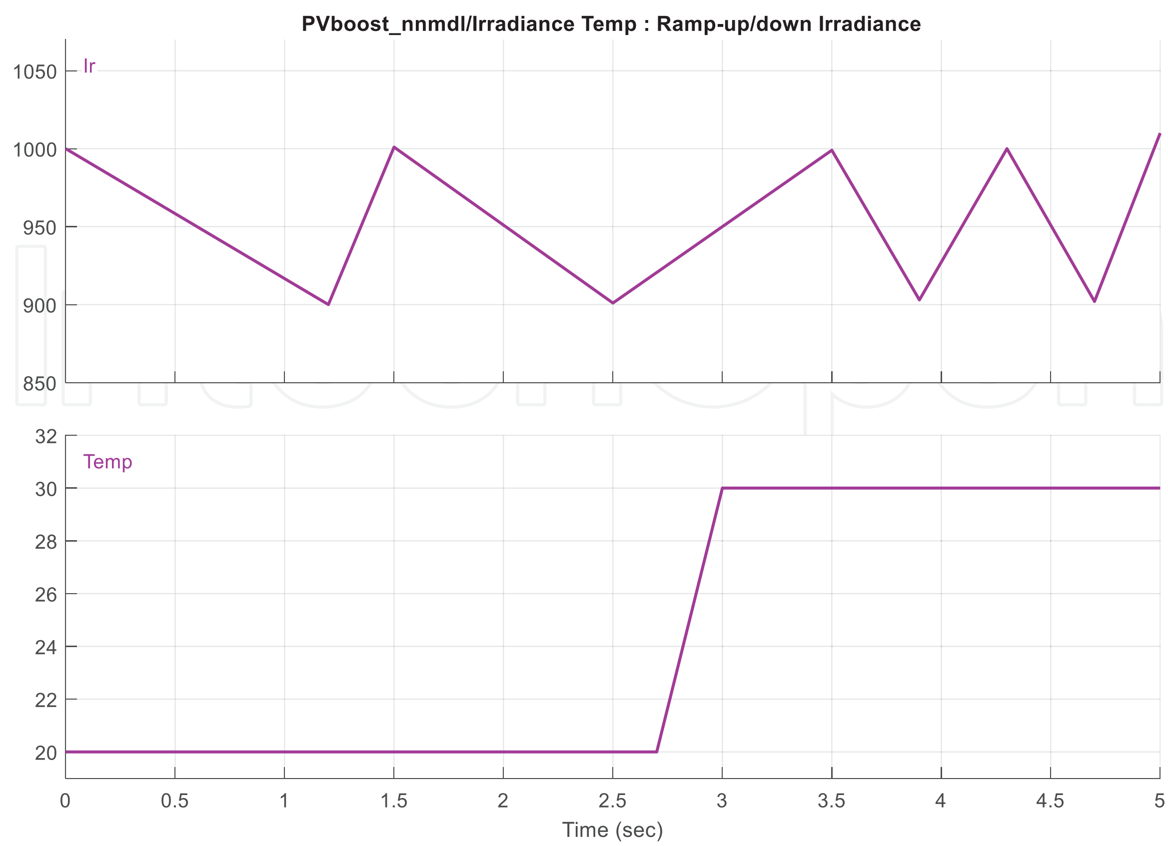

Figure 5.
Irradiation level and ambient temperature change of PV array.

Simulation studies are realized under irradiation and ambient temperature change of the PV array; these changes are sketched in **Figure 5**.

Output voltage under reference change is obtained as in **Figure 6** by the nonlinear controller. Reference voltage is changed from 150 V to 200 V at 1 s, from 200 V to 250 V at 2 s, from 250 V to 200 V at 3 s, and from 200 V to 150 V at 4 s. Under the reference changes, output voltage is achieved as desired with −0.2 V at 150 V reference, −0.5 V at 200 V reference, −1.1 V at 250 V reference, steady-state error. Also, steady-state error is obtained as 0.015 s at 150 V reference, 0.005 s at 200 V

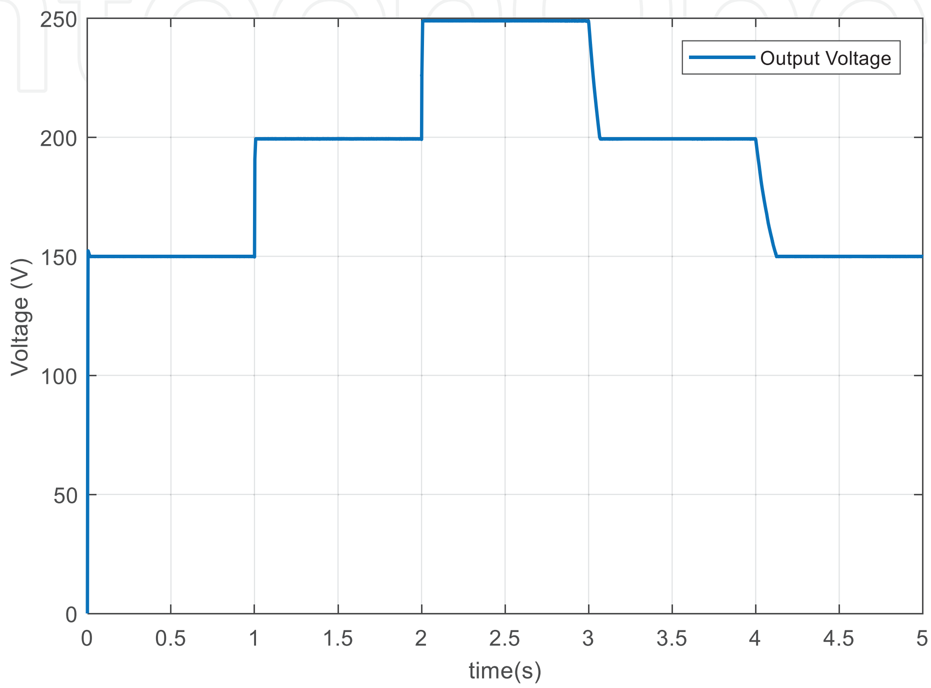

Figure 6.
Output voltage of interleaved boost DC-DC converter.

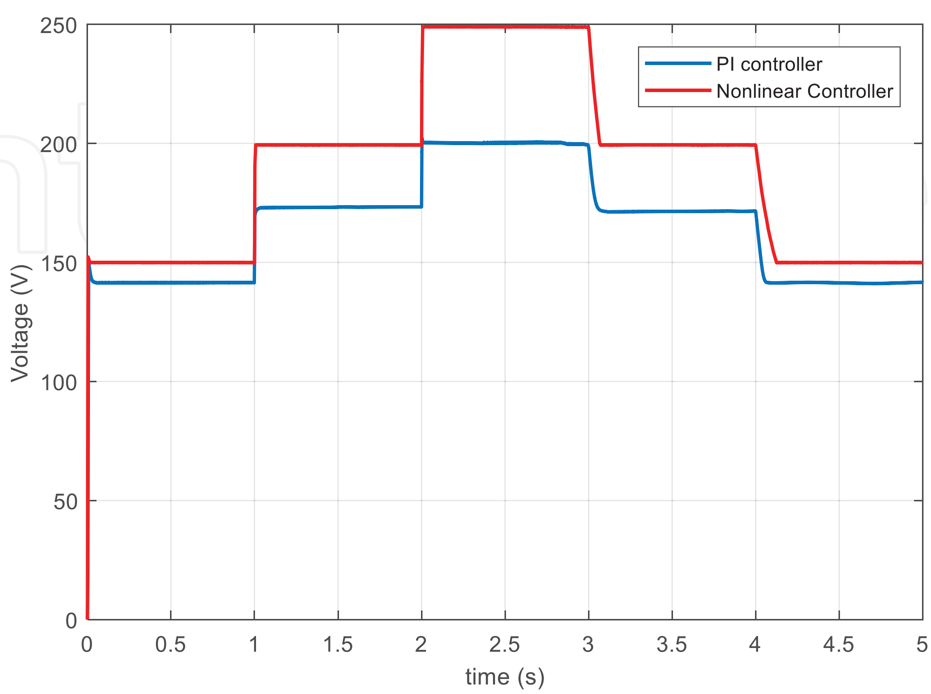

Figure 7.
Output voltage of interleaved boost DC-DC converter with PI and nonlinear controller.

reference, 0.008 s at 250 V reference, and 0.07 s at second 200 V reference, 0.125 s at second 150 V.

In order to compare the performance of the nonlinear controller, the same system is controlled by the PI controller. In **Figure 7**, the results obtained by both controllers are sketched.

Figure 7 shows that by PI controller desired reference voltages are not acquired, however, nonlinear controller provides desired reference voltages.

4. Conclusions

In this chapter, firstly feedback linearization techniques, including input-state and input–output linearization, are described. Then input–output linearization technique is applied to interleaved boost converter that is connected to the output of the PV array. Besides, solar irradiation and ambient temperature of PV array are changed during the simulation study.

The result obtained by the nonlinear controller is compared to the linear PI controller. It is determined by the study that the nonlinear controller ensures the desired output voltage with a maximum 1.1 V steady-state error and 0.125 s settling time, whereas the linear PI controller could not provide the reference voltage as it desired.

In future work, the implementation of the study is targeted to be carried out.

Conflict of interest

The authors declare no conflict of interest.

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