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PID based on a single artificial neural network algorithm for DC-DC boost converter

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ABSTRACT

This research focuses on developing a proportional integral derivative controller based on a single artificial neural network (PID-SANN). The proposed control strategy drives the direct current (DC-DC) boost converter output voltage to follow the desired reference value. This controller calculates the PID gains via a learning algorithm based on an artificial single-neuron network, which overcomes the computational complexity of PID gains using analytical methods and automatically adjusts the controller parameters. The developed PID-SANN method offers the boost converter the appropriate duty ratio, which permits controlling the output voltage value despite fluctuations in the resistive load or input voltage. The obtained results confirm that the developed method can successfully surmount the constraints of conventional PID controllers and direct the output voltage of the considered DC-DC converter to follow the required value precisely.

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1. INTRODUCTION

The use of direct current (DC-DC) boost converters is expanding because of their high efficacy, adaptability, small size, and low cost. It is found in battery chargers, electric vehicles, home appliances, and aerospace. Additionally, it plays a crucial role in using renewable energy conversion technologies, including fuel cells, wind turbines, and solar photovoltaic systems [1]-[3].

The nonlinearity model of the boost converter makes control difficult. Thus, it requires employing reliable, quick control adaptable to systems with changing structures. A feedback control loop is utilized in the adjustment process of the duty ratio to keep a constant output voltage under varying operating conditions [4], [5]. The classical proportional integral derivative (PID) controller is generally used to control boost converters as an efficient method due to its simple design and high dependability [6], [7]. Nevertheless, PID gains are synthesized based on an exact mathematical model. Any changes in the system necessitate rebuilding the model and adjusting the gains of the new controller. As a result, it is not an ideal control strategy when dealing with nonlinear systems because it cannot guarantee good performance [8], [9].

To ameliorate the performance of conventional PID controllers, many researchers have invested significant efforts in designing nonlinear controllers that have been applied to boost converters. For example, the authors in [10], [11] have suggested utilizing a sliding mode control (SMC) for driving the DC-DC converter. This method is reliable under plant uncertainties and outside disturbances. However, variable structure control using the sliding mode approach has some drawbacks, the most notable of which is the chattering phenomenon. This phenomenon causes output voltage response to oscillating when the duty ratio fluctuates in the stable state [12], [13].

Reseachers [14]-[16] describe the use of a fuzzy logic controller (FLC) to control a boost converter's output voltage. Nevertheless, the FLC controller is completely based on human knowledge and experience. This means that its fuzzy rules and fuzzy membership function need to be designed in a very organized way. An adaptive backstepping controller for a boost converter type has been presented in [17], [18]. Despite its simplicity, it also faces limitations and obstacles in the implementation phase. A feedback linearization control for the boost converter has been discussed in [19], [20]. The proposed technique assures robustness in terms of tracking and speed. Nonetheless, in [19], the impacts of parasitic elements on electrical components are ignored. Li and Chen [20], the suggested controller cannot be employed in a broad range of variations due to an increased overshoot.

On the other hand, hybrid methods based on traditional PID have been proposed to optimize its parameters [21]-[23]. The particle swarm optimization algorithm has been investigated in [22] to construct a PID controller that manages the output value of the DC-DC boost converter. However, this method has trouble reducing high-frequency oscillations. A genetic algorithm (GA) based on a PID controller has been proposed and implemented in [22], [23]. However, the primary problem of this technique resides in the fact that it highly depends on the system dynamic.

Recently, other methods have been proposed based on artificial neural networks (ANN) and applied in many control and modeling domains, such as robotics, power systems and big data. It notes that the artificial neural network has several types and architectures like single artificial neural network (SANN) [24], multilayer neural networks (MNNs) [25], recurrent neural networks (RNNs) [26], radial basis function neural networks (RBFNNs) [27], stochastic configuration networks (SCNs) [28]. Because of their extensive capabilities for approximation, adaptability, and parallel processing, these techniques are appealing for modeling and managing nonlinear systems. The SANN has a simple structure, faster learning and improved approximation capabilities. Due to these advantages, it has been applied to control many systems, such as intelligent sensors, DC motors and fixed-wing UAVs [24], [29], [30].

In this context, the main goal of this study is to create a novel PID control scheme that utilizes a single artificial neural network approach (PID-SANN). The designed control scheme is employed to push the boost converter's output voltage to track exactly the desired reference value under various operational conditions. First, the adaptability of single neuron and online control parameters adjustment is utilized to adapt to the changes under different operating conditions. Secondly, a constant K is provided to adjust the system response characteristics related to its stability and fast performance. Finally, the proposed control method can be used easily to solve the problems experienced by conventional PID controllers. The rest sections of this study are structured as follows: The dynamic model of the considered DC-DC boost converter is presented in the section 2. A single artificial neural network algorithm-based adaptive PID is introduced in the section 3. In the fourth part, the obtained results are discussed and a comparison between the developed PID-SANN technique and the traditional one is presented. Finally, a conclusion is provided to end this work.

2. DC-DC BOOST CONVERTER SYSTEM

A DC-DC boost converter is an electrical power circuit that converts one direct voltage into a higher direct voltage. It consists of an ultra-fast diode, a MOSFET transistor, and two energy storage devices (inductor and capacitor). A schematic of the considered boost converter topology is presented in Figure 1. The DC-DC converter is inherently a non-linear system. It needs a transfer function before applying the analysis techniques to linear systems [3], [31]. In this research, the small-signal method is used to describe the transfer function of the considered system as (1):

$$G(s) = \frac{\hat{V}_o(s)}{\hat{u}(s)} = \frac{V_i}{RC(1-D)^2} \frac{\frac{R(1-D)^2}{L} - s}{s^2 + \frac{s}{RC} + \frac{(1-D)^2}{LC}} \tag{1}$$

where the circumflex accent represents a small variation around the operating point. V_o denotes the output voltage. L, C, and R signify inductance, capacitor, and resistive load. D represents the duty ratio. V_i represents the input voltage.

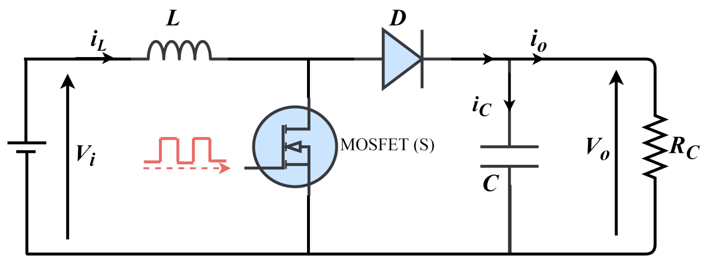


Figure 1. DC-DC boost converter schematic

3. PID-SANN ALGORITHM DESIGN

The fundamental goal is to provide a control unit that is simple, dependable and requires little computing effort. The proposed algorithm can be implemented on a boost converter system with low set-up needs, which users that have limited knowledge of control theory can employ. The SANN method is utilized primarily to determine the values of the three ideal gains K_p, K_i and K_d of the PID controller. Figure 2 represents the parallel structure of the PID controller [32].

As from the diagram bloc, V_d is the desired voltage and V_o is the measured voltage. The continuous time of a PID controller can be expressed using the (2):

$$u(t) = K_p e(k) + K_i \int_0^t e(t)dt + K_d \frac{e(t)}{dt} \quad (2)$$

the relation represents the discrete time of PID controller expression as (3):

$$u(k) = K_p e(k) + K_i T \sum_{j=1}^{k} e(j) \frac{K_d}{T}(e(k) - e(k-1)) \quad (3)$$

the corresponding incremental PID controller can be expressed as (4):

$$u(k) = u(k-1) + K_p\left(e(k) - e(k-1)\right) + K_i e(k) + K_d\left(e(k) - 2e(k-1) + e(k-2)\right) \quad (4)$$

where K_p, K_i and K_d are the proportion, integration and differential coefficients, respectively. $e(k)$ is the error between the measured and desired values.

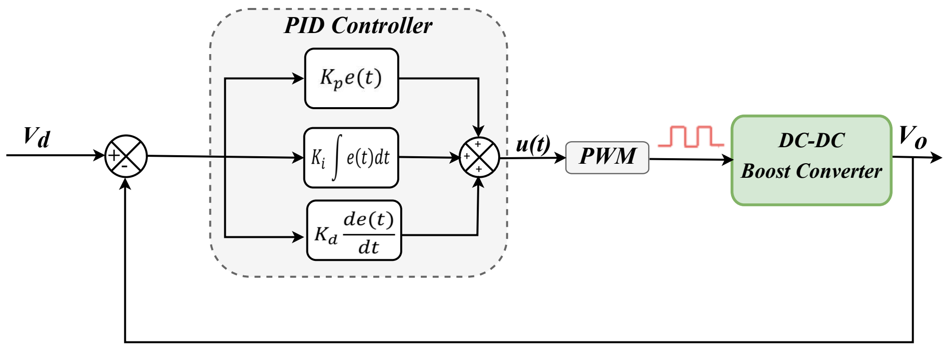


Figure 2. PID controller structure

It is clear that the classical PID with fixed parameters suffers from a K_p K_i and K_d gains tuning problem to achieve the optimal control. Furthermore, system features can change over time, necessitating re-adjusting these parameters. Therefore, this method cannot provide high-performance control when operating conditions vary. To overcome these drawbacks, a combination of a single neuron network and a conventional

PID controller is presented. The diagram bloc of the developed PID-SANN controller for the boost converter system is depicted in Figure 3.

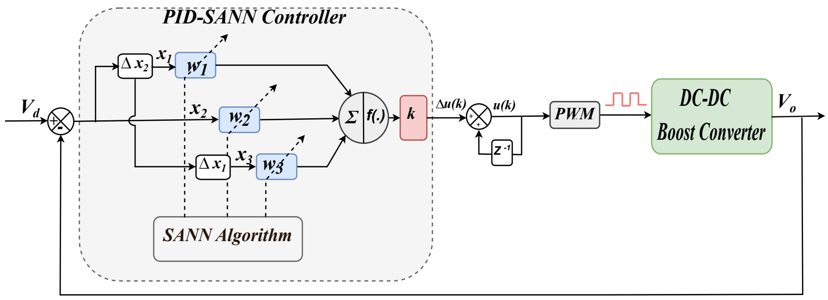


Figure 3. Diagram bloc of PID-SANN controller

According to the Figure 3, the input of the PID-SANN controller is the error that can be written as follows: $e(k) = V_d(k) - V_o(k)$ and the output is the incremental duty ration $\triangle u(k)$. The (4) can be reformulated as (5):

$$u(k) = u(k-1) + K_p x_1(k) + K_i x_2(k) + K_d x_3(k) \quad (5)$$

at k^{th} sampling time the control signal $u(k)$ is obtained through:

$$u(k) = u(k-1) + \triangle u(k) \quad (6)$$

$$\triangle u(k) = K_p x_1(k) + K_i x_2(k) + K_d x_3(k) \quad (7)$$

where $x_1(k)$, $x_2(k)$ and $x_3(k)$ are:

$$\begin{cases} x_1(k) = \triangle x_2 = e(k) - e(k-1) \\ x_2(k) = e(k) \\ x_3(k) = \triangle x_1 = e(k) - 2e(k-1) + e(k-2) \end{cases} \quad (8)$$

to get the summing function, these variables are multiplied by the weights $w_i(k)$.

$$\triangle u(k) = K\left(w_1(k)x_1(k) + w_2(k)x_2(k) + w_3(k)x_3(k)\right) \quad (9)$$

where K is the single neuron proportional coefficient, and $K > 0$.

The PID-SANN algorithm minimizes the error between the closed-loop system reference voltage and its measured voltage. Using the mean square error (MSE) relationship, we can define the cost function $g(k)$ at sampling times $(k + 1)$ as (10):

$$g(k+1) = \frac{1}{2}(V_d(k+1) - V_o(k+1))^2 = \frac{1}{2}(e(k+1))^2 \quad (10)$$

the gradient descent approach is used to minimize the cost function $g(k)$, which is defined as (11):

$$w_i(k) = w_i(k-1) - \eta_i \nabla w_i g(k) \quad (11)$$

where $\nabla w_i g(k)$ represents the gradient vector of $g(k)$ and $\eta_i(k)$ illustrates the hidden layer learning rate. It indicates that the direction of the weight update is along the negative gradient. Thus, using the chain rule, the formula for updating the weight is as (12)-(14):

$$\triangle w_i(k) = -\eta_i \nabla w_i g(k) = -\eta_i(k)\frac{\partial g(k)}{\partial w_i(k)} \quad (12)$$

$$\triangle w_i(k) = -\eta_i \left(\frac{\partial g(k)}{\partial y(k)}\right)\left(\frac{\partial y(k)}{\partial u(k)}\right)\left(\frac{\partial u(k)}{\partial w_i(k)}\right) \tag{13}$$

$$\triangle w_i(k) = \eta_i K e(k) \frac{\partial y(k)}{\partial u(k)} x_i(k) \tag{14}$$

in theory, the expression $\frac{\partial y(k)}{\partial u(k)}$ can be approximated by the following form $\frac{Dy(k)}{Du(k)}$. The term $\frac{\partial y(k)}{\partial u(k)}$ is uncertain, therefore, may be replaced by signal function, the calculated error can be compensated by adjusting learning rate $\eta_i(k)$. The (14) can be expressed as (15):

$$\triangle w_i(k) = \eta_i K e(k) x_i(k) sgn\left(\frac{\partial y(k)}{\partial u(k)}\right) \tag{15}$$

before calculating the control variable, the weights must be normalized to guarantee the convergence and robustness of PID-SANN. Hence, the (9) can be formulated as:

$$\triangle w_i(k) = \eta_i K e(k) x_i(k) u(k) \tag{16}$$

the new value w_i is:

$$w_i(k+1) = w_i(k) + \triangle w_i(k) \tag{17}$$

$$\triangle w_i(k) = K \sum_{i=1}^{3} \bar{w_i}(k) x_i(k) \tag{18}$$

and,

$$\bar{w_i}(k) = \frac{w_i(k)}{\sum_{i=1}^{3} \mid w_i(k) \mid} \tag{19}$$

with:

$$\begin{cases} w_1(k+1) = w_1(k) + \eta_p e(k) u(k) x_1(k) \\ w_2(k+1) = w_2(k) + \eta_i e(k) u(k) x_2(k) \\ w_3(k+1) = w_3(k) + \eta_d e(k) u(k) x_3(k) \end{cases} \tag{20}$$

where η_p is the proportional learning rate, η_i is the integral learning rate and η_d is the differential learning rate. The obtained PID-SANN controller parameters can be stated as:

$$\begin{cases} K_p = K\bar{w_1}(k) \\ K_i = K\bar{w_2}(k) \\ K_d = K\bar{w_3}(k) \end{cases} \tag{21}$$

the (21) shows that the weight parameter can be adjusted by continuous learning. This indicates that the PID-SANN can adapt to nonlinear control. As shown, the adjustable coefficients of PID-SANN controller are scale coefficient K, learning rate η_i and initial weight coefficient value $w_i(0)$ where:

- The initial value of the weight parameter is chosen randomly.
- The scale coefficient K is taken as a fixed value initially and then can be adjusted based on the simulations and experiment results.
- The learning rate η_i is chosen precisely in order to achieve better performance in terms of response and overshoot.

4. RESULTS AND DISCUSSION

In order to verify the validity and effectiveness of the developed PID-SANN controller, several simulation tests were run under various operating situations. This is employed to control the output voltage of the DC-DC boost converter to follow the desired voltage value. The Simulink model utilized is shown in Figure 4.

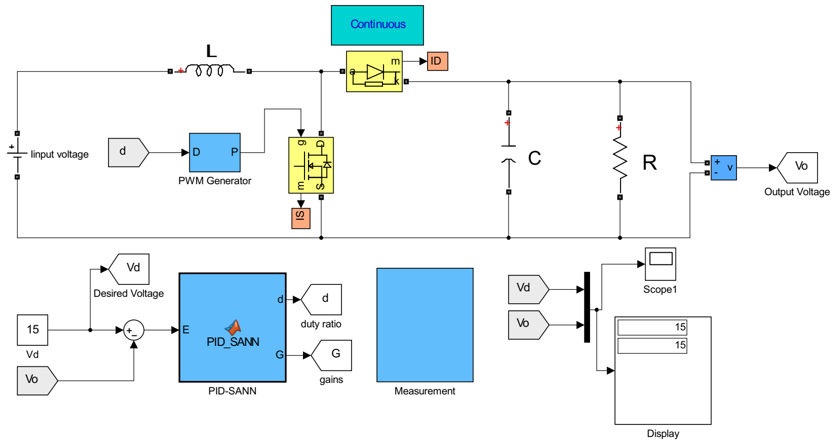


Figure 4. Model Simulink for boost converter

The first simulation test is carried out with a constant desired voltage value ($V_d = 10$ V) and input voltage ($V_{in} = 5$ V). The output voltage's response is shown in Figure 5. This result shows that the output voltage rapidly follows the desired voltage without overshoot. It also demonstrates that the time needed to respond to the reference model is very short ($8 \times 10^{-3}s$).

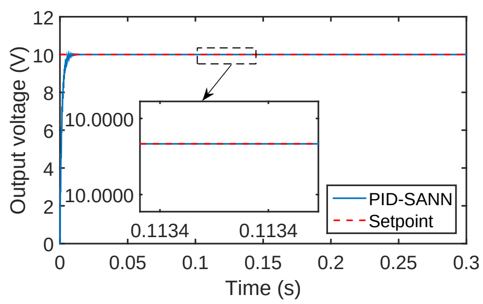


Figure 5. Output voltage response for $V_d = 10$ V

The second simulation test is performed for a multi-step reference and constant input voltage ($V_{in} = 5$ V). Figure 6 represents the simulation results for a multi-step voltage reference, which includes four subfigures. The output voltage response is displayed in Figure 6(a) while the response of PID gains is respectively given in Figure 6(b), Figure 6(c), and Figure 6(d).

Through these results, it is clear that the developed controller can drive the boost converter to track exactly the desired voltage. In addition, It is possible to mention that the PID-SANN controller has excellent tracking performance. In addition, we note that the PID parameters change automatically in accordance with the changes in the desired voltage.

The following simulation is performed to examine the effectiveness of the suggested technique under sudden variations in operating conditions. The input voltage is supposed to be changed from 5 to 10 V at $t = 0.05$ s, whereas the resistive load is assumed to be changed from 10 to 25 Ω at $t = 0.1$ s. Figure 7 shows the simulation results under input voltage variation, which includes the output voltage response and the PID gains in Figure 7(a) and Figure 7(b), respectively. Figure 8 displays the simulation results under load variation, which also contains the output voltage response and the PID gains in Figure 8(a) and Figure 8(b), respectively.

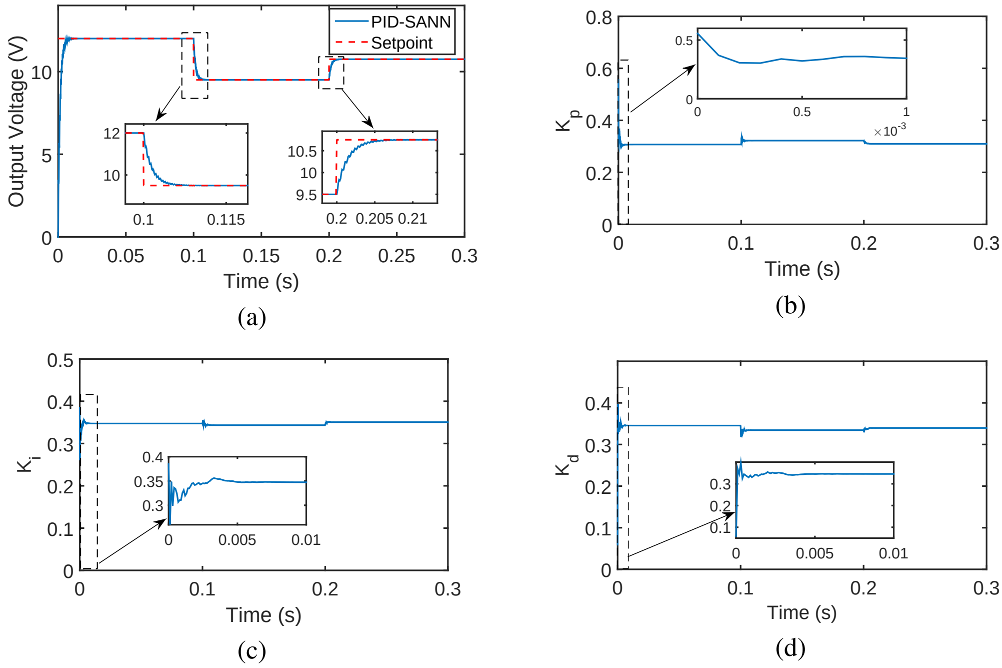


Figure 6. Simulation results for multi-step voltage recurrence (a) output voltage response, (b) K_p gain variation, (c) K_i gain variation, and (d) K_d gain variation

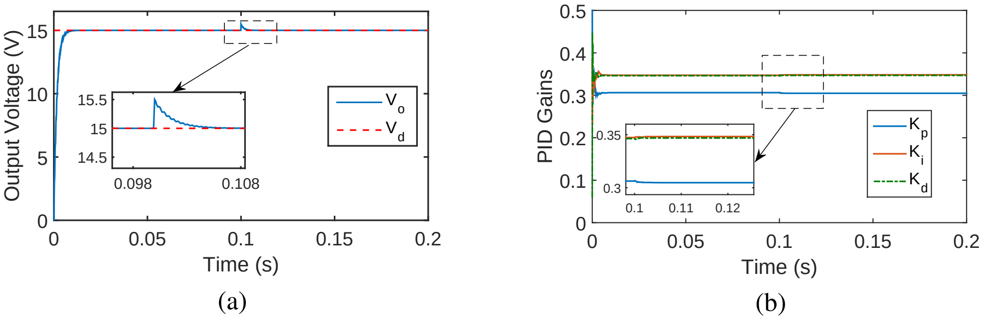


Figure 7. Simulation results under input voltage variation (a) output voltage response and (b) PID gains variation

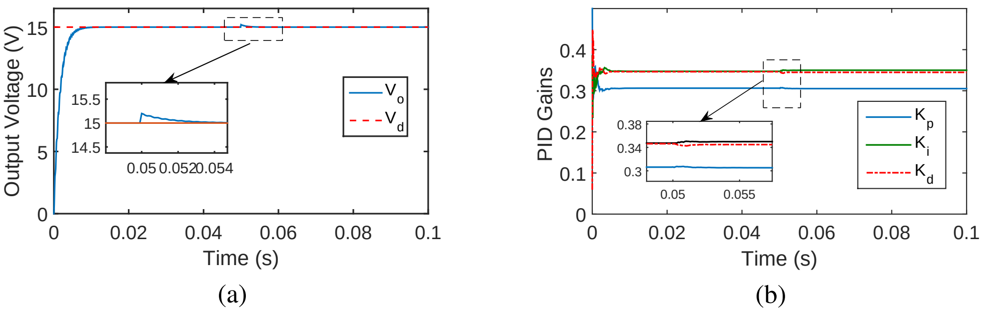
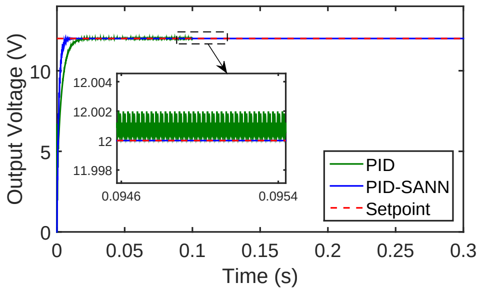
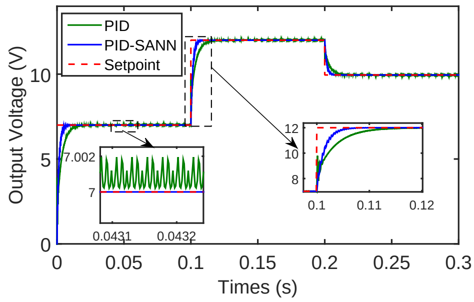


Figure 8. Simulation results under load variation (a) output voltage response and (b) PID gains variation

These results obtained under changes in input voltage or load indicate that the response of the output voltage perfectly matches its reference with a quick reaction and good performance without any overshoot in voltage. Note that this test is done in a very short time ($t = 0.1$ s), which confirms the effectiveness and strength of the proposed PID-SANN controller. It is also shown that the PID parameters automatically adapt to sudden input voltage variations or load changes. It can be said that the developed method operates professionally and successfully under any sudden changes. The last simulation test is conducted to compare the developed technique PID-SANN with the traditional one. Figure 9 shows the comparison between PID and PID-SANN controllers, which includes two subfigures. The output voltage responses of both controllers, PID and PID-SANN, with a fixed and variable reference voltage, are displayed in Figure 9(a) and Figure 9(b), respectively.



(a)



(b)

Figure 9. Comparison between PID and PID-SANN controllers response for (a) $V_d = 12$ V and (b) multi-step reference

The performances of the considered and compared controllers are summarised in Table 1. These results show that the conventional PID suffers from oscillations around the reference voltage and a slow response under sudden changes in the operating conditions compared to the proposed controller, which provides better quality, regarding rise time, overshoot, and settling time. It is obvious from this that the proposed PID-SANN technique gives superior performance in terms of speed response, overshoot, and following precision.

Table 1. Performances comparison between PID and PID-SANN controllers

Controller	PID	PID-SANN
Rise time (s)	12x10^{-3}	7x10^{-3}
Settling time (s)	15x10^{-3}	9x10^{-3}
Overshoot %	0.2	0.01

5. CONCLUSION

This paper proposes an intelligent PID method by using the ANN technique devoted to the DC-DC boost converter. Many tests conducted under various operating conditions revealed that the self-adaptive PID based on a single neuron network controller has much superior control performance than the conventional PID controller. In addition, the developed technique drives the converter output voltage to follow the required depending on variation in input voltage or resistive load. The proposed PID-SANN controller is characterized by its simplicity, ease of application, high reliability and robust performance. It can produce a fast response with a very low overshoot at start-up and a better steady-state response. The acquired findings attest to the effectiveness and reliability of the suggested technique.

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