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The comparison study of PI and Sliding Mode control techniques for Buck-Boost converters

Kayan tipli denetim ve PI kontrol tekniklerinin Düşüren-Yükselten dönüştürücü için karşılaştırılması

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Abstract

This paper compares the performance of a Sliding Mode Control (SMC) and Proportional-Integral (PI) controller under different voltage and load conditions. The study's findings underscore the need to account for load variations in system designs and to continuously seek system optimization irrespective of the controller type chosen. PI controller demonstrates effectiveness under certain circumstances. However, significant drops in voltage and current during abrupt load changes are obtained. On the other hand, SMC enables superior adaptability, efficiently managing voltage transients and load variations without any electrical disturbances, thereby maintaining system stability. A comparative analysis further emphasizes the SMC's superior time response and robustness against reference voltage changes. Consequently, SMC is proven to be a preferable choice over the PI controller in systems experiencing frequent voltage and load variations. However, both controllers achieve the potential for further response time optimization and stability.

Keywords: Buck-Boost converter, Power conversion, PI control, Sliding mode control

Öz

Bu makalede, farklı voltaj ve yük koşulları altında Kayan Tipli Denetim Kontrol (SMC) ve Oransal-İntegral (PI) kontrolörün performansı karşılaştırmaktadır. Çalışmanın bulguları, sistem tasarımlarındaki yük değişimlerini hesaba katarak ve seçilen kontrolör tipine bakılmaksızın sürekli olarak sistem optimizasyonu arama ihtiyacının altını çizmektedir. PI kontrolörü belirli koşullar altında etkinlik göstermektedir. Ancak, ani yük değişimleri sırasında gerilim ve akımda önemli düşüşler elde edilebilmektedir. Öte yandan SMC, geçici voltaj geçişlerini ve yük değişimlerini herhangi bir elektriksel bozulma olmadan verimli bir şekilde yönetmektedir. Böylece sistem kararlılığını koruyarak SMC daha üstün uyarlanabilirlik sağlamaktadır. Karşılaştırmalı analiz ayrıca SMC'nin üstün zaman tepkisini ve referans voltajı değişikliklerine karşı etkinliğini göstermektedir. Sonuç olarak, SMC'nin, sık gerilim ve yük değişimlerinin yaşandığı sistemlerde PI denetleyiciye göre daha çok tercih edilebilir olduğu kanıtlanmıştır. Ancak her iki kontrol yöntemi de etkili sistem cevabı ve kararlılığını yakalayabilecek seviyede performans göstermiştir.

Anahtar Kelimeler: Düşüren-Yükselten dönüştürücü, Güç dönüşümü, PI kontrol, Kayan tipli denetim kontrol

1 Introduction

DC-DC buck-boost converters are crucial components in various electrical and electronic systems, extending beyond photovoltaic applications. They can both increase and decrease the voltage level of an input power source, thus providing a regulated output voltage that aligns with the requirements of the connected loads. This feature is especially critical in scenarios where the input voltage is erratic or inconsistent [1-5].

Among the different control strategies used to govern the operation of these buck-boost converters, Proportional-Integral-Derivative (PID) control and sliding mode control are often implemented. The PID control strategy relies on a feedback mechanism from the output voltage, enabling adjustments to maintain stable output. Conversely, Sliding Mode Control (SMC), being robust and not reliant on feedback, is less sensitive to system disturbances [6-9].

The objective of this study is to identify the more effective control strategy between PID control and sliding mode control, as well as to offer valuable insights that could guide future improvements in the design and operation of DC-DC buck-boost converters. This comparison is expected to significantly contribute to the field of power electronics and control systems. This paper aims to compare the performance of PI and SMC. The analysis will focus on their ability to regulate output voltage under varying input conditions and their overall impact on the efficiency of the system into which they are integrated.

This paper is organized as follows: In Section 2, Literature review is presented. Then, DC-DC Buck-Boost

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converter details are given in Section 3. Section 4 includes evaluation of proposed control techniques; PI and Sliding Mode Control. In Section 5, results are presented for each control methods. Finally, the main ideas of the paper are summed up, and Conclusions are presented in Section 6.

2 Literature review

This Section includes the research that has already been done on the use of Sliding Mode Controller, PID, and Second Order Sliding Mode to regulate the Buck-Boost converter. Switch-mode power sources often employ DC-DC converters. The popularity of these switch-mode DC-DC converters is growing for a variety of reasons, including their suitability for a variety of applications. This indicates that the main issues with switching converters are analysis, control, and stability.

In power electronics, buck-boost converters are often used to modulate the output voltage by adjusting the duty cycle of the switching signal. The converter may step up or decrease the input voltage, depending on the demands of the load [10-13]. The performance of buck-boost converters has recently been addressed by several control approaches, such as SMC, PID control, and second-order sliding mode control (SOSMC).

Sliding mode control is a reliable control method that performs well in tracking and disturbance rejection in the face of uncertainties and disturbances. The sliding mode controller forces the sliding variable to reach and stay on a sliding surface to guarantee that the system output follows the required reference signal [14-16]. The system is made to be insensitive to disturbances and uncertainty by the sliding surface. Several studies have suggested the use of sliding mode control for voltage regulation in the context of buck-boost converters.

For the interleaved DC-DC boost converter, [17] presents a fuzzy logic sliding mode controller. The sliding mode controller ensures resilience against all changes, and fuzzy logic is employed to eliminate the chattering problem induced by the sliding controller, which increases efficiency and lowers error, voltage, and current ripples. The suggested approach outperforms traditional sliding mode controllers when subjected to input and reference voltage fluctuations. The period of adjustment might be detrimental [18].

In another study performance and features of fuzzy based sliding mode controller is presented. It has been shown that sliding mode control is suited for boosting DC-DC conversion and offers reliable voltage management. The resultant controller/converter system can maintain the load, no matter how the input line voltage or other variables vary [19]. [20] demonstrates that DC-DC converters have a strong potential for enhancing dynamic performance with the implementation of Sliding Mode Control. DC-DC converters and other VSS converters function well with this nonlinear control scheme. SMC's key advantage over conventional linear control strategies is its resilience in the face of line, load, and parameter changes [21].

In [22], the effectiveness of sliding mode control for the regulation of DC-DC converters is compared with traditional linear control with regard to transient characteristics. According to research, sliding mode control is better capable of delivering steady transient responses in a variety of operational scenarios. The main benefits are resilience and dependability in the presence of parameter, line, and load uncertainty.

According to [23], the general performances and characteristics of three different types of controllers for a DC-DC boost converter in continuous conduction mode are compared: the Sliding Mode (SM) controller, the PI controller, and the proportional integral derivative controller. The pulse width modulation-based sliding mode controller outperforms the PID controller in the presence of fluctuating input and load voltages. A sliding mode controller can help to reduce the nonlinearity and instability of power converters.

According to [24], second-order sliding mode control can maintain the fundamental characteristics of normal sliding mode control while eliminating chattering and ensuring smooth, or at least piecewise smooth, control. The approach also offers more accurate estimations of switching latency.

3 DC-DC Buck-Boost converter

The DC-DC buck-boost converter, shown in Figure 1, is an electronic circuit capable of either stepping up (increasing) or stepping down (decreasing) the input direct current (DC) voltage to a desired output DC voltage. This type of converter is widely used in various applications including battery-operated devices, electric vehicles, portable electronics, and power supply systems. It provides a stable output voltage, which is crucial for these systems, regardless of variations in input voltage [25]. The main structure of a buck-boost converter includes an inductor, two switches (usually MOSFETs or transistors), and two diodes. The converter operates in two distinct modes, given in following Sub-Sections.

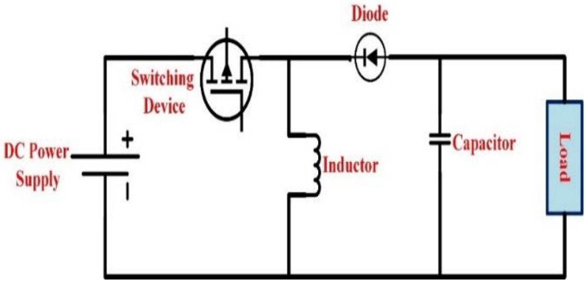

Figure 1. DC-DC Buck-Boost converter scheme [25]

3.1 Buck mode

In Buck mode operation, the converter functions as a step-down converter, decreasing the input voltage. One switch is closed (ON), and the other is open (OFF). The closed switch allows current to flow through the inductor, thereby storing energy in its magnetic field. The diode associated with the open switch is reverse-biased, which prevents current from flowing through it. When the switch is opened, the inductor's magnetic field collapses, and the energy is transferred to the output capacitor through the forward-biased diode. As a result, the output voltage is obtained lower than the input voltage in this mode.

3.2 *Boost mode*

In Boost mode operation, the converter functions as a step-up converter, increasing the input voltage. The roles of the switches and diodes are reversed compared to the previous mode. Current passes through the inductor when the switch is closed, storing energy in its magnetic field. Reverse-biasing the diode connected to the closed switch stops current from passing through it. When the switch is opened, the inductor's magnetic field collapses, and the stored energy triggers a voltage spike across the inductor. This voltage spike, when combined with the input voltage, results in a higher voltage across the diode. Consequently, the diode becomes forward-biased, allowing current to flow through it and charge the output capacitor.

In this mode, the output voltage is higher than the input voltage. Depending on the duty cycle, which is the ratio of the switch ON duration to the overall switching period, the converter can either run in boost or buck mode. The converter works in boost mode when the duty cycle is greater than 0.5 and in buck mode when it is less than 0.5.

Buck-boost converters offer versatility by providing both step-up and step-down functionality. However, they also come with some disadvantages, such as increased complexity compared to standalone buck or boost converters, reduced efficiency at high output currents, and the generation of Electromagnetic Interference (EMI) due to the switching action.

4 PI and Sliding Mode Control

In this Section, PI and Sliding Mode Control details are presented and evaluated.

4.1 *PI control for DC-DC Buck-Boost converter*

The PI controller is a popular feedback control algorithm used to regulate various processes in numerous applications. In the context of a DC-DC buck-boost converter, the PI controller can be employed to maintain a constant output voltage, even when the input voltage or load conditions change. The PI controller adjusts the duty cycle of the switching signal applied to the buck-boost converter based on the error between the desired output voltage (reference voltage) and the actual output voltage. The PI controller consists of two components: proportional (P), and integral (I), each with its respective gains (K_p and K_i) [26].

By means of a methodical tuning approach aiming at maximizing the performance of the control system. With an eye on reducing the error between the expected output and the actual system response and guaranteeing stability and resilience, these coefficients have been determined using the Ziegler-Nichols technique.

Ziegler-Nichols method offers a methodical methodology to adjust the PI controller settings. First, this approach determines the ultimate gain (K_u), that is the gain at which the system starts to oscillate with a constant amplitude. It also establishes the final period (T_u), the temporal interval of these steady oscillations. The Ziegler-Nichols approach employs certain formulae to compute the proportional (K_p), integral (Ki) gains depending on once determined values for K_u and T_u and given in Equation (1-2).

$$K_p = 0.45 \times K_u \tag{1}$$

$$K_i = 2 \times K_p / T_u \tag{2}$$

Table 1 shows the Ziegler-Nichols parameters for tuning PI controller.

Table 1. PI and Ziegler-Nichols parameters

Parameter	Value
Ultimate Gain (K_u)	0.72
Ultimate Period (T_u)	0.05
Proportional Gain (K_p)	0.324
Integral Gain (K_i)	13

The output signal is sent to the PI controller together with the reference signal and the output real output voltages, which are measured as fed back. The rising edge pulsed output-controlled output signal is sent to the chopper, where the controlled output is obtained in the form of a duty cycle presented in Equation (3).

$$u(t) = K_p e(t) + K_i \int_0^T e(t)dt \tag{3}$$

Steady-state error, rising time, overshoot, settling time, and robustness are a few of the important performance factors that directed the tuning effort. The constant-state error has been reduced to guarantee that, without continuous offsets, the system output closely matched the reference signal. While the maximum overrun has been lowered to prevent too great changes in the response of the system, the rise time has been changed to balance a quick reaction with little overshoot. The settling period has been also adjusted to guarantee rapid stabilization of the system around the target value. At last, resilience has been taken into account to guarantee the controller could efficiently manage changes in system characteristics and disturbances.

4.2 *Sliding mode control (SMC) for DC-DC Buck-Boost converter*

Sliding Mode Control (SMC) is an advanced control technique that has been applied to various power electronics systems, including DC-DC buck-boost converters. SMC is a robust and efficient method for controlling non-linear systems with uncertainties, as it can provide a fast-transient response and high accuracy under varying conditions.

The basic idea behind SMC is to force the system's state to move along a pre-defined sliding surface in the state space, which guarantees desired system behavior. The state flows along the sliding surface to the intended equilibrium point after it reaches it. To implement SMC for a DC-DC buck-boost converter, two steps are realized, as defined in the following Sub-sections:

4.2.1 Sliding surface

In this step, sliding surface (S) that represents the desired dynamic behavior of the converter is defined. A common choice for the sliding surface in a buck-boost converter is presented in Equation (4) as follows:

$$S = \left(V_{out} - V_{ref}\right) + \lambda * \left(V_{out\_dot}\right) \tag{4}$$

where V_{out} is the output voltage, V_{ref} is the reference output voltage, λ is a positive constant, and V_{out_dot} is the derivative of V_{out} with respect to time.

4.2.2 Control law

Control law forces the system state to the sliding surface and ensures that it remains there. The control law should drive the sliding surface (S) to zero. The sliding line determines the switching frequency for the SM control, which relates to the on/off shifting of the converter switch. Equation (5) are defined for the switch function.

$$S = C_1 x_1 + C_2 x_2 = C^T x = 0 \tag{5}$$

where, x_1 and x_2 are the state variables, and C_1 and C_2 are the coefficients that determine how these state variables combine to form the sliding surface.

Careful determination of the coefficients $C1$ and $C2$ of the intended Sliding Mode Control (SMC) has been done to satisfy the dynamics and control criteria of the system. These coefficients have been chosen with consideration for system properties to guarantee that the control system achieves the intended performance. The mathematical model of the system has been first established, and the sliding surface has been defined considering the nonlinear characteristics of this model. Performance requirements including speed, stability, and system overshoot of the sliding surface are considered throughout design. These criteria allowed the coefficients $C1$ and $C2$ to be found, thereafter evaluated and refined iteratively in simulations. The aim of this technique has been to guarantee that the system stays stable during the steady-state and rapidly approaches the sliding surface during the transient state. The coefficients $C1$ and $C2$ are tuned to correspond with the dynamic characteristics and performance criteria of the system. Consequently, used to balance system performance, stability, and robustness, the values of $C1$ and $C2$ are 0.01 and 0.2 respectively.

The control law is implemented using a switching mechanism that toggles the control input u based on the value of the sliding surface S. The sliding surface dictates the switching frequency for the sliding mode control, which directly influences the on/off shifting of the converter switch. The switching function is described by Equation (6):

$$u = \begin{cases} 1 = ON \quad when\ S > k \\ 0 = OFF \quad when\ S < k \\ previous\ state, otherwise \end{cases} \tag{6}$$

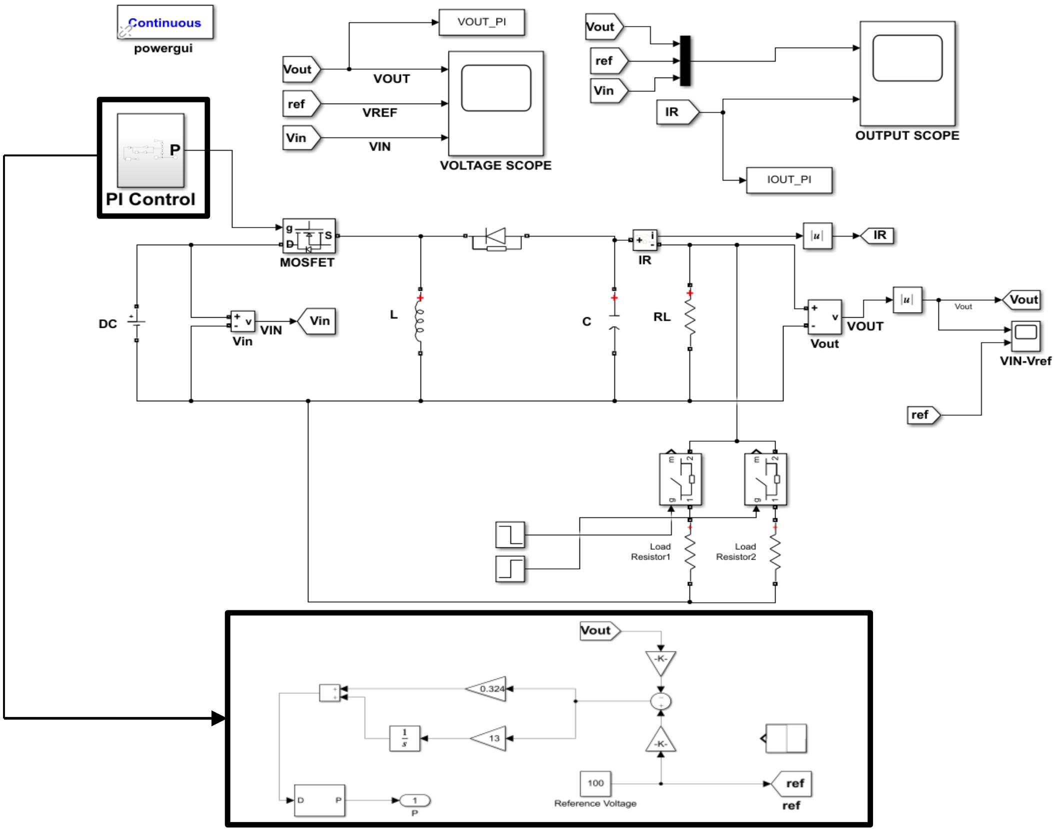

Figure 2. PI controlled Buck-Boost converter simulation scheme

where, k represents a threshold value that determines the switching boundary. When the sliding surface S exceeds k, the control input u switches to ON (1). On the other hand, the control input turns off (0) when$S$ is less than$k$. Should S be near to k, the control input maintains its former condition to avoid needless switching.

The correct operation of the sliding mode controller depends on this switching technique as it guarantees that the system state stays on the sliding surface, therefore attaining the intended control goals. Table 2 shows the buck-boost system parameters.

Table 2. Buck-boost system parameters

Number	Parameter	Values
1	Input Voltage	100 V
2	Capacitance	2 mF
3	Inductance	1 μH
4	Duty cycle	0.5
5	C_1, C_2	0.01, 0.2
6	K_p, K_i	0.324, 13

5 Results and discussions

In this paper, MATLAB/Simulink having a user-friendly graphical interface and allows for easy implementation of control algorithms is used to simulate a Buck-Boost converter with proposed control methods. In Figures 2-3 simulation scheme is given for PI and SMC respectively. The details of the proposed system parameter are presented in Table 1.

Figure 4 illustrates the comparison of output voltage variations under changes in reference voltage for both the PI controller and the SMC. Reference voltage is 100 V between zero and two second, and is changed as 150 V between two and four second, and is applied to simulation as 50 V after four second. SMC exhibits a high-level time response without any overshoot or damping. However, the PI controller is affected by changes in the reference voltage.

The PI controller also experiences overshoot and damping when the reference voltage changes, with a slower settle-down time compared to the SMC. With changing the reference voltage in the PI and SMC and comparing depending on the output voltage, it is clearly observed that the SMC maintained a constant value while the PI responded by exceeding and a delay in returning to a steady state.

Figure 5 shows performance comparison of the output voltages under load variations for SMC and PI controller. Load is changed from 100 to 200 ohms between two and four second, for other time intervals load is 100 ohms. Therefore, output voltage is observed. SMC performs better dynamic response for load variation with desired 100 V constant output voltage.

It is noted that the decrease in current according to Ohm's law, and the SMC appears well without sparks and with smooth transition during the change in load. This refers to the system's ability to handle sudden changes without causing a sudden voltage spike or drop, which could cause a voltage drop at the output and could be ignored because of undistorted voltage and fast dynamic response. In addition, In Figure 6, the load current comparison is realized with the changing output load of the proposed PI and SMC, as stated in Figure 5. It is observed that SMC is outstanding with a faster and more stable response of output current, without overshooting or damping unlike PI control.

In Figures 4-6, it is clear that SMC is outstanding method when compared to PI control. Output voltage settle time is effectively small, and dynamic response performance is superior for reference voltage change and load change.

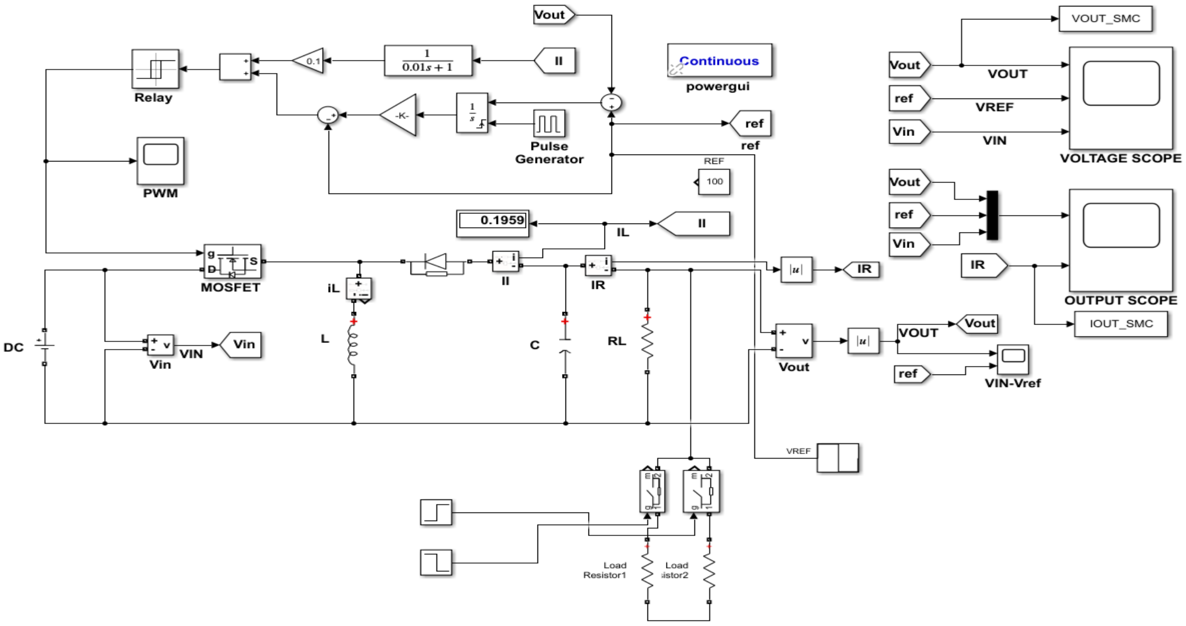

Figure 3. SMC controlled Buck-Boost converter simulation scheme

Based on many performance criteria, PI and Sliding Mode Control (SMC) performance has been evaluated. First, it has been found by evaluating the transient reaction that SMC reacts much quicker than PI control. For PI control, for example, the settling time measured at 0.06 seconds after a change in the reference voltage; SMC finished the operation in only 0.02 seconds. Regarding overshoot, SMC kept this overrun at a much lower 1% level whereas the PI control system reacted to abrupt changes in the reference voltage with a 10% overshoot. Examining the settling time, SMC shortened the duration to 0.02 seconds whereas PI control took 0.08 seconds to settle at the new reference value. Moreover, in terms of stability and robustness, SMC showed better performance during load fluctuations, displaying consistent behavior and fast recovery free from abrupt voltage dips as opposed to PI control. Though SMC needed somewhat more control effort than PI control, this effort has been tuned to provide a more consistent and quick output. While SMC regularly maintained the output voltage at 100 V, during load variation testing it has been shown that the output voltage under PI control had variations, declining from 100 V to 90 V before returning to the setpoint.

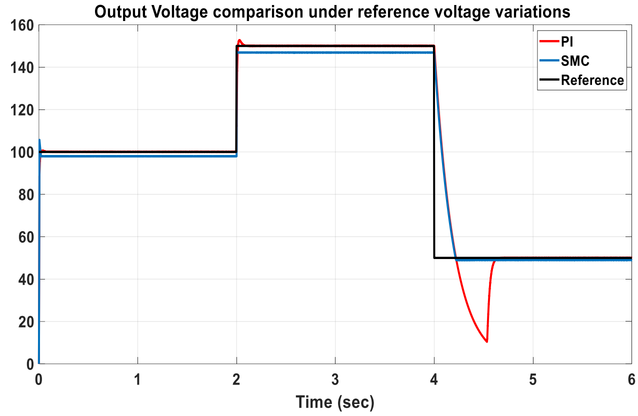

Figure 4. Output voltage comparison under reference voltage variations

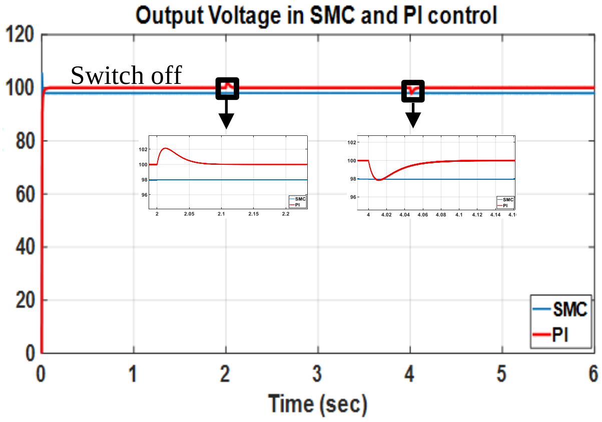

Figure 5. Output voltage comparison under load variations

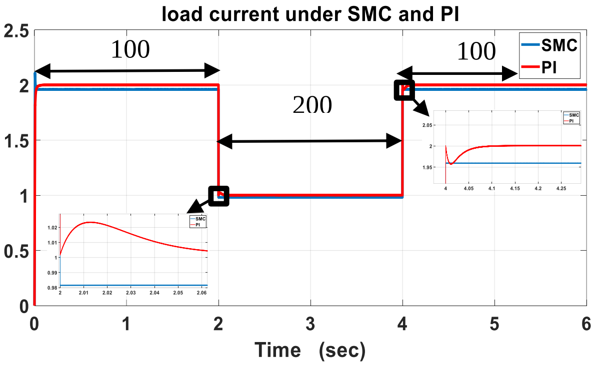

Figure 6. Load current comparison under load variations

6 Conclusions

This paper provides critical insights into the performance of PI controller and Sliding Mode Control (SMC) under varying voltage and load conditions. The SMC have demonstrated remarkable adaptability and robustness, effectively handling voltage transients and load variations. Even amid dynamic load changes, the SMC have managed to maintain consistent output without any electrical disturbances, attesting to its superiority in ensuring system stability. The comparative analysis further emphasizes the superior performance of the SMC over the PI controller. Despite the PI controller being effective in certain scenarios, some limitations such as overshoot during reference voltage alterations and slower settling time have been observed. On the other hand, the SMC have displayed a heightened time response and robustness against reference voltage changes, making it an optimal choice in scenarios with dynamic load changes. Given these findings, the study strongly recommends adopting the SMC over the PI controller, particularly in systems facing frequent voltage and load fluctuations, thanks to its superior performance and adaptability. While both the PI controller and SMC have the potential for further improvement, the SMC's effectiveness in managing voltage and load changes have outperforms and provides valuable insights for the design and operation of Buck-Boost converter under diverse conditions.

Conflict of interest

The authors affirm that none of their known financial conflicts of interest or personal connections could have appeared to impact the research presented in this study.

Similarity rate (iThenticate): 19 %

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