

Sliding Mode Based Nonlinear Control of a Three-Level NPC-Type DC-DC Bidirectional Converter for HV Applications

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ABSTRACT

This paper proposes the design and a comparative study of three sliding mode-based controllers—sliding mode control (SMC), fuzzy logic sliding mode control (Fuzzy-SMC), and ANFIS sliding mode control (Anfis-SMC)—applied to a newly designed DC-DC isolated bidirectional converter featuring a three-level neutral point clamped (3L-NPC) topology. Utilizing single phase shift (SPS) modulation enabled by a simplified analytical model, the controllers demonstrate strong robustness against load disturbances and input voltage variations, while ensuring accurate reference voltage tracking in both Boost and Buck modes. Comparative analysis shows that all three controllers outperform the traditional PI controller across most performance metrics. Voltage balancing is effectively maintained through an auxiliary inductive circuit. The investigated control schemes are validated via MATLAB-Simulink simulations, confirming their suitability for the efficient control of the studied converter.

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1. INTRODUCTION

Power electronic converters are variable-structure engineering systems and, as such, are challenging to control using traditional linear control techniques. Moreover, the loads supplied by these converters are often nonlinear and highly unpredictable. Among various nonlinear control algorithms reported in the literature, sliding mode control (SMC) has become popular due to its proven efficiency in handling complex nonlinearities in real systems, thanks to the fact that it is not sensitive to external perturbations; moreover it exhibits capability of converging at finite-time [1]. Combining sliding mode control with two other nonlinear algorithms—namely fuzzy control and ANFIS control—allows harnessing the benefits of two nonlinear controllers within a single control scheme [2].

Bidirectional DC–DC converters (BDCs) are increasingly used across a broad range of applications, including energy storage systems, uninterruptible power supplies, and electric vehicles [3]. Moreover, the field of electric vehicles is rapidly developing and heavily utilizes BDCs, notably in battery charging systems [4], [5]; other application areas include renewable energy systems and DC power grids [3], [6]. High-voltage direct-current (HVDC) grids are preferred over traditional high-voltage alternating-current (HVAC) transmission systems due to their flexibility, reliability, and reduced losses. Compared with conventional AC grids, DC systems enable effective control of active and reactive power flow, improved power transmission, and enhanced system stability. In addition, they enable easier and more efficient storage of electrical energy, facilitating better integration of diverse energy sources at potentially lower costs and with improved power quality [7]. However, the development of DC grids requires, among other technologies, DC–DC conversion

systems [8]. These systems must be properly controlled to ensure optimal energy flow regardless of load and line conditions.

Regarding their topologies, two main families of DC-DC converters can broadly be distinguished: non-isolated topologies and isolated topologies [3], [8]. Non-isolated DC-DC converters transfer power without magnetic isolation, which makes them more susceptible to faults. In contrast, isolated DC-DC converters incorporate magnetic isolation and can achieve high voltage gain thanks to the transformation ratio of the isolation transformer, making them well-suited for high-voltage applications [9].

One of the most popular topologies for isolated DC-DC conversion is the Dual Active Bridge (DAB) [10]. However, despite the high voltage gain offered by the isolation transformer, DAB converters are not always suitable for HVDC applications due to their limited voltage withstand capability. There have been several attempts in the literature to address the problem of limited DC voltage output. References [11], [12], and [13] propose a three-level NPC dual-active-bridge DC-DC bidirectional converter topology, consisting of a single-phase 3L-NPC DC-AC converter on the primary side of the isolation transformer and a 2L AC-DC converter on the secondary side. However, the DC output is limited to a maximum value of 6.6 kV [12]. In [14] and [15], a 3L NPC DAB with 3L NPC converters on both sides of the isolation transformer is proposed; nevertheless, the DC output does not exceed 7 kV.

In terms of control strategies, the DAB converter has been extensively researched using nonlinear control techniques, particularly sliding-mode control (SMC) algorithms. For instance, reference [16] discusses an adaptive SMC control algorithm applied to a bidirectional DAB utilizing extended phase-shift modulation (EPSM). Reference [17] introduces current and voltage regulation of a DAB converter based on a double-integral SMC approach. Sliding-mode control methods have also been applied to DAB converters in battery energy storage systems, as seen in reference [18]. Additionally, fuzzy-logic methods for DAB control are explored in references [19] and [20], while reference [21] focuses on optimizing DAB performance for electric vehicle charging using an adaptive neuro-fuzzy inference system (ANFIS) algorithm.

Despite significant advancements in multilevel DAB converters, it is noted that nonlinear control algorithms remain underexplored. Current research primarily emphasizes optimal switching and modulation techniques for multilevel DAB converters [15], [22].

In this context, the contribution of our paper lies in an investigative study on three sliding-mode-based nonlinear control algorithms applied to a 3L-NPC-based multilevel bidirectional DAB using a single phase-shift (SPS) switching technique. Our findings aim to fill the gap in the literature regarding nonlinear control strategies for multilevel DAB converters, providing a comprehensive analysis and potentially extending the operational capabilities beyond those previously reported.

The structure examined in this paper consists of two superimposed single phase 3L NPC based multilevel DAB. Each stage includes a two-level DC-AC converter on the left side of the isolation transformer and a single-phase three-level neutral point clamped converter on the right side, as illustrated in Fig. 1. The 3L-NPC topology has the advantage of providing a large value of DC output voltage as compared to two level converters [23], [24],[25]. Consequently, the superposition of two single-phase 3L-NPC AC-DC converters at the structure's output enables a significant increase in the DC output voltage, making the topology suitable for high-voltage (HV) applications.

This study investigates the application of three sliding mode control (SMC)-based algorithms to a bidirectional DC-DC converter employing a neutral point clamped (NPC) topology with galvanic isolation. The control strategies analyzed include: standard Sliding Mode Control (SMC), Adaptive Neuro-Fuzzy Inference System-enhanced SMC (ANFIS-SMC), and Fuzzy Logic-based SMC (Fuzzy-SMC). Numerical simulations conducted within the Matlab/Simulink environment demonstrate that all three control schemes confer substantial robustness against load variations, input voltage fluctuations, and reference tracking errors. Nonetheless, each control methodology exhibits distinct characteristics, which are comprehensively evaluated through a comparative analysis.

The primary contributions of this work are summarized as follows:

- A simplified approach for analyzing the 24-switch NPC-based converter structure, enabling the use of single-phase shift modulation despite the topology's complexity.
- The robust design of three nonlinear controllers related to sliding mode control.
- A rigorous comparative analysis of the three SMC-based controllers, highlighting their respective strengths and limitations.

The paper is structured as follows: in Section 2, details of the proposed research methodology are given. In Section 3, simulation results are presented and discussed. Section 4 finally exposes concluding remarks and suggest possible future research directions.

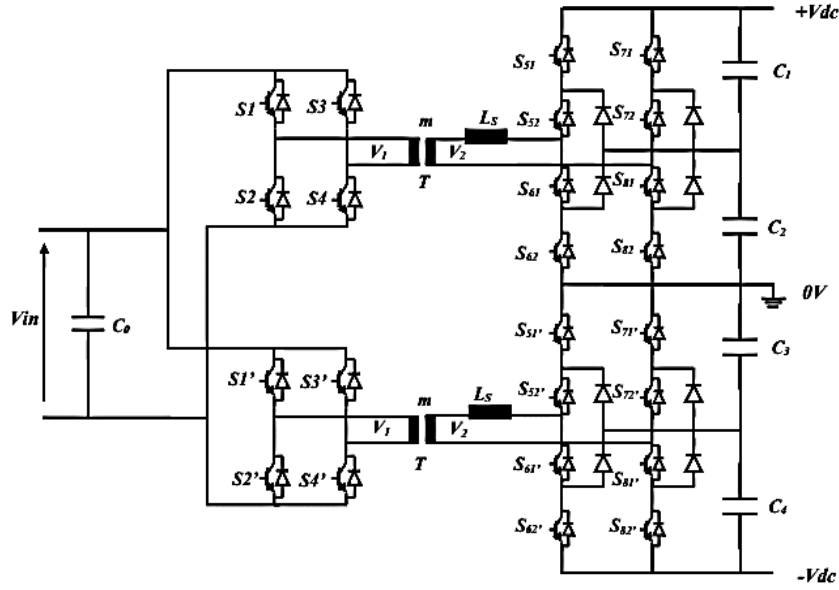


Figure 1. Topology of the DC-DC bidirectional converter.

2. RESEARCH METHOD

In this section, a study of the converter is carried out, followed by the presentation of the proposed control schemes.

2.1. Study of the converter

The topology of the converter consists of two identical stages: an upper stage and a lower stage. We will analyze only one stage; therefore, this study can be extended to the other stage of the converter. Each stage comprises a single-phase 2-level DC-AC converter on the left side of the isolation transformer and a single-phase 3-level NPC AC-DC converter on the right side. The inductance L_s enables power transfer from one side of the isolation transformer to the other. This inductance introduces a phase shift γ between primary and the secondary voltages of the isolation transformer; m is the transformation ratio. V_1 and V_2 are the primary and the secondary voltages respectively. Let f_s the switching frequency of the converter, the phase shift γ or phase difference time of the converter is defined as follows [26], [27].

$$\gamma = D \times T_s \quad (1)$$

With

$$D = \frac{T_{on}}{T_s} \quad (2)$$

And

$$T_s = \frac{1}{2f_s} \quad (3)$$

D is the phase shifted ratio ratio; T_s is the switching period, T_{on} is the duration of conduction of a switch in one cycle of functioning of the converter. Each leg of the 3-level NPC converter as illustrated in Fig. 2, has three possible switching states. Each switching state corresponds to one of the three voltage levels, as presented in Table 1. However, given the fact that the transformer is fed by a 2-level DC-AC converter which provides only two voltage levels per cycle, we decide to eliminate one of the three switching states of the NPC converter, so as to have the same number of switching states for the two-level converter and the three level converter. This is achieved by commanding the switches of the three-level converter in pairs instead of commanding them individually as depicted in Table 2. The consequence is that switching state N°2, which corresponds to the voltage $V_{AN} = 0$ is simply eliminated. This consideration permits the use of the single phase switch (SPS) modulation technique just as it could be done for a dual active bridge (DAB) converter, therefore reducing considerably the complexity of the converter's control.

Table 1. Possible switching states in one leg of a 3L-NPC converter.

Switching states	S1	S2	S3	S4	VAN
1	1	1	0	0	$V_d/2$
2	0	1	1	0	0
3	0	0	1	1	$-V_d/2$

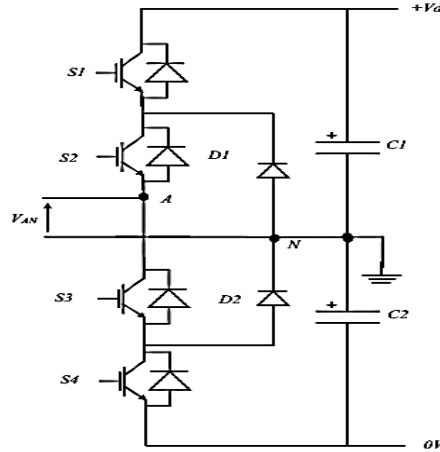


Figure 2. A leg of a 3L-NPC converter

Table 2. Steady state operation of the converter on one cycle of its functioning.

	[t 0;t 1]	[t 1;t 1+DT s]	[t 1+DT s;t 2]	[t 2;t 2+DT s]
S1;S4	1	1	0	0
S2;S3	0	0	1	1
S51;S52	1	0	0	1
S61;S62	0	1	1	0
S71;S72	0	1	1	0
S81;S82	1	0	0	1

An open loop simulation of one stage of the converter with a resistive load of $1k\Omega$ and $L_s = 1mH$ gives the results presented in Fig. 3.

V_1 and V_2 are the primary and the secondary voltages respectively; I_L is the current in the inductance L_s and V_L is the voltage across it. The phase shift between V_1 and V_2 , which can visually be noticed when V_1 and V_2 are superposed, allows power transfer from any of the two sides of the isolation transformer to the other.

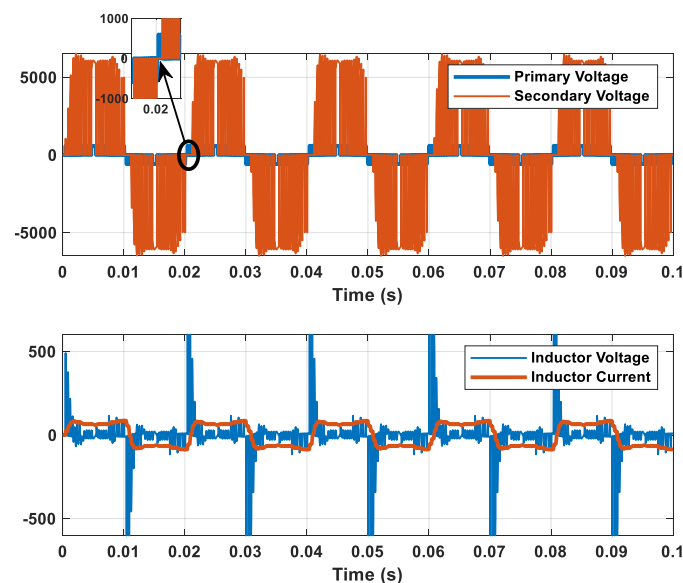


Figure 3. Open loop simulation of one stage of the converter: the phase shift is highlighted

2.2. Design of nonlinear controllers

The three proposed control schemes have a common general structure, depicted in Fig. 4 below. In this section, the design of the controllers is carried out.

2.2.1. Sliding mode controller

The general condition that guaranties the existence of a sliding mode controller as recalled in [28] is as follows:

$$u = \frac{1}{2}(1 + \text{sign}(S)) = \begin{cases} 1 & \text{if } S > 0 \\ 0 & \text{if } S < 0 \end{cases} \quad (4)$$

Where S is the sliding surface, u is the control variable. The sliding surface S should be selected such that, during sliding mode, the following conditions are verified: $S = 0$ and $\dot{S} = 0$. The unified condition that ensures sliding mode existence is given as follows [29].

$$S \cdot \dot{S} < 0 \quad (5)$$

The sliding surface is chosen as [29]:

$$S = \delta_1(V_{ref} - V_{out}) + \delta_2 \int_0^t (V_{ref} - V_{out}) \quad (6)$$

V_{out} is the output voltage and V_{ref} is the output reference voltage. δ_1 and δ_2 are respectively the proportional and the integral coefficients of the sliding surface.

$$\dot{S} = -\delta_1 \frac{dV_{out}}{dt} + \delta_2 (V_{ref} - V_{out}) \quad (7)$$

Let i_c the current flowing in the capacitive branch of the converter i_c can be written as follows:

$$i_c = C \frac{dV_{out}}{dt} = I_{Ls} - I_o \quad (8)$$

Where C is the total output capacitance, I_{Ls} is the current in the inductance Ls and I_o is the load current. From Eq. (6) we can deduce the following:

$$\frac{dV_{out}}{dt} = \frac{I_{Ls} - I_o}{C} = \frac{I_{Ls}}{C} - \frac{V_{out}}{CR} + \frac{D(1-D)V_{in}}{4fCLs} \quad (9)$$

With

$$I_{Ls} = \frac{(-2D+1)V_{in} - V_{out}}{2R} \quad (10)$$

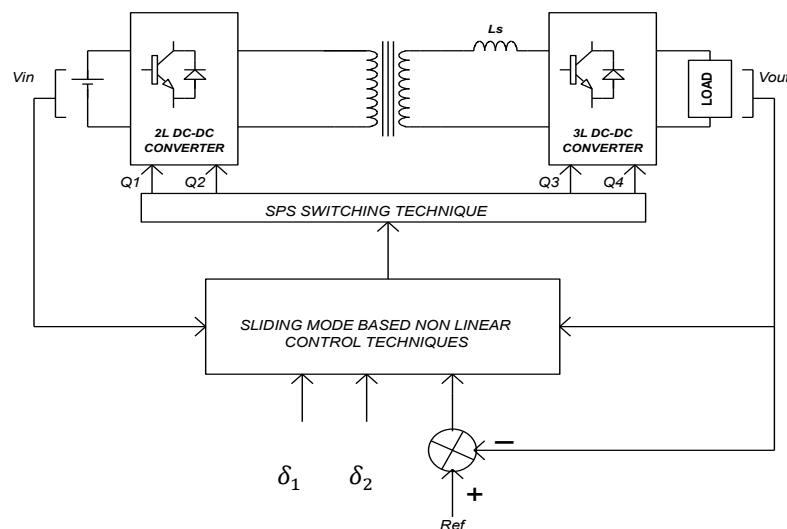


Figure 4. General structure of control schemes

The phase shifted ratio D at equilibrium is determined by substituting Eqs. (8) and (9) into Eq. (7). At steady state ($\frac{ds}{dt} = 0$); by solving the quadratic equation obtained with respect to D , we have:

$$D_0 = \frac{1 - \frac{4fLs}{R} + \sqrt{\left(\frac{4fLs}{R} - 1\right)^2 - 8fLs + \frac{3V_{out}}{V_{in}R} + \frac{2C\delta_2}{V_{in}\delta_1}(V_{ref} - V_{out})}}{2} \quad (11)$$

D_0 is the positive solution out of the two solutions arrived at. The settling time is tuned by judiciously choosing sliding surface coefficients δ_1 and δ_2 . So, these coefficients are selected such as to obtain the best possible settling time for the output voltage V_{out} .

Stability of the sliding mode controller can be verified using the Lyapunov function Q defined as follows [28].

$$Q(S) = \frac{1}{2}S^2 \quad (12)$$

With $Q(S) > 0$ for $S > 0$. The asymptotic stability of the system is obtained when:

$$\frac{dQ(S)}{dt} = \frac{1}{2} \frac{d}{dt} S^2 = \dot{S} \cdot S \leq -\varepsilon |S| < 0 \quad (13)$$

ε is a real constant having a positive value, that enable to assess the rate of convergence of the trajectory of the sliding surface. This inequality permits to demonstrate that all trajectories converge towards the sliding surface. This therefore allows to confirm – if the inequality is verified – that the sliding surface is reachable and stable [30]. Plugging Eqs. (6) and (7) into (13) permits to confirm that the system is stable according to Lyapunov.

2.2.2. ANFIS Sliding mode controller

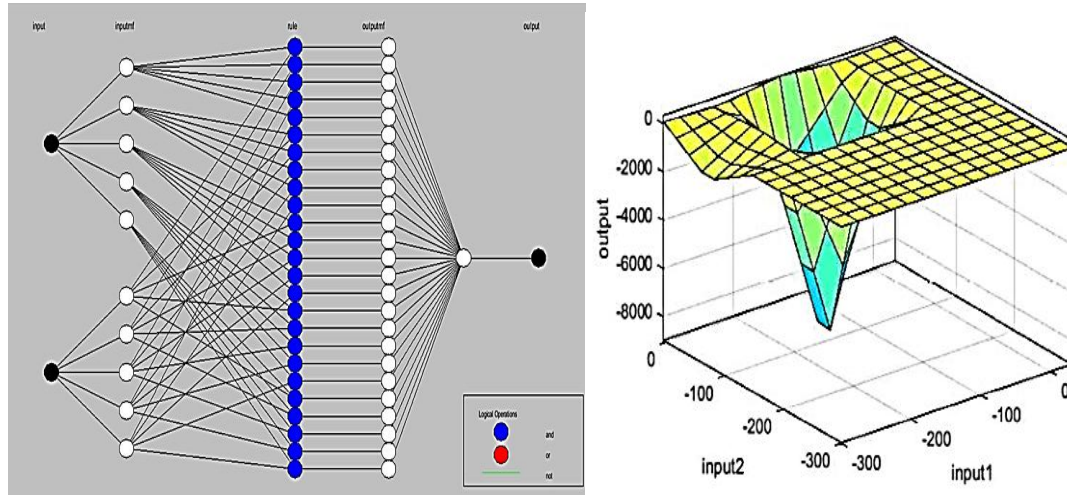
The phase shift ratio (D) is regulated via an Adaptive Neuro-Fuzzy Inference System (ANFIS), which integrates a fuzzy logic algorithm having an architecture with a five-layer artificial neural network. The inputs to the neuro-fuzzy controller comprise the current phase shift ratio ($D(n)$) at discrete time (tn) and its rate of change (ΔD). The controller adaptively determines the membership functions' parameters and the rule base governing the relationship between input and output variables, in an optimized manner, based on the training dataset through a dedicated learning algorithm [31].

$$Input1 = D(n) \quad (14)$$

$$Input2 = \Delta D = D(n) - D(n-1) \quad (15)$$

Where $D(n)$ is the phase shifted ratio at a the n th iteration and $D(n-1)$ is the phase shifted ratio at the $(n-1)$ th iteration.

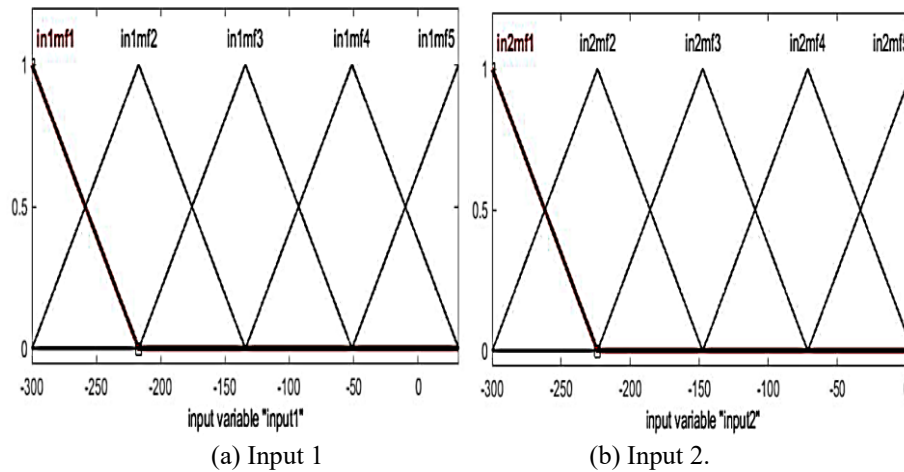
The ANFIS algorithm utilises a first-order Sugeno fuzzy model having a structure with five-layer artificial neural networks. The ANFIS architecture consists of two inputs, each associated with five triangular membership functions. The system has one output characterized by twenty-five linear membership functions and twenty-five fuzzy rules, as illustrated in Fig. 5(a). A hybrid learning algorithm is utilized, comprising two scans: a forward scan and a backward scan. During the forward scan, the node outputs propagate through the network up to the fourth layer, and the resulting parameters are estimated using sequential least squares method. In the backward scan, the error signal spreads backward, and the premise parameters are updated via gradient descent. This process is known as the backpropagation learning algorithm [31]. Figures 5(b) and 6 depict the output surface and the input membership functions of the investigated ANFIS algorithm, respectively.



(a) Structure of ANFIS.

(b) Output surface

Figure 5. Structure of the proposed ANFIS controller and its output surface.



(a) Input 1

(b) Input 2.

Figure 6. Input membership functions of the ANFIS controller

A proportional-derivative (PD) block is added to the ANFIS sliding mode control loop to enhance its performance. The PD controller combines proportional and derivative actions: the proportional action reduces the static error and increases the rapidity of the system, while the derivative action improves stability, although it does not affect the static error.

2.2.3. Fuzzy logic Sliding mode controller

Fuzzy control offers a structured methodology that enables the representation, the manipulation, and the implementation of human knowledge on how to control a system. The fuzzy controller comprises four main components: (i) the rule-base which contains a set of rules specifying how to optimally control the system. (ii) The inference unit which assesses which control rules are pertinent at the current time and deduce the convenient control action for the plant. (iii) The fuzzification interface which translates input values into fuzzy sets, enabling interpretation and comparison with the rules in the rule base. And (iv) the defuzzification unit which transforms the fuzzy decisions generated by the inference unit into control signals to be applied to the plant [32]

The fuzzy logic controller designed in this work has two input variables: the first is the phase-shifted ratio D generated by the sliding mode controller block, and the second is ΔD , which represents the change in that phase-shifted ratio. The controller has one output, u , which is sent to the SPS modulation algorithm.

Triangular membership functions, designated by NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small) and PB (Positive Big), are used for both phase shifted ratio and the change in phase shifted ratio. They are presented in Fig. 7 below.

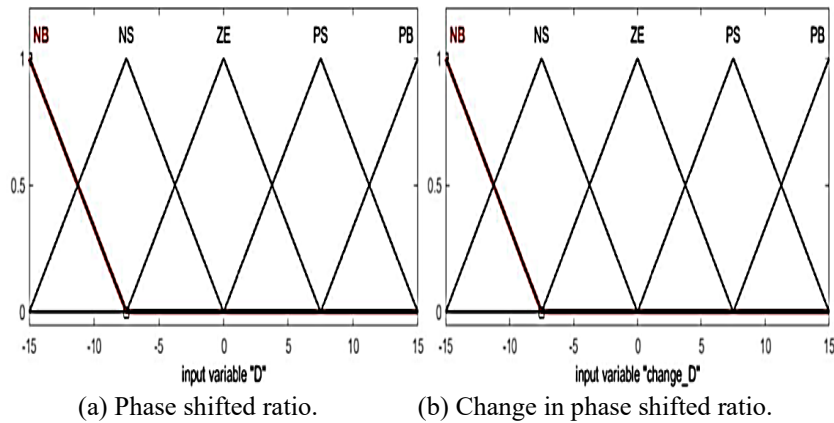


Figure 7. Fuzzy controller input membership functions.

The output surface of the fuzzy logic controller, corresponding to the Rule Base given in Table 3, is represented in Fig. 8.

Table 3. Rule base of the proposed fuzzy logic controller

		D				
		NB	NS	ZE	PS	PB
ΔD	NB	PB	PB	PS	ZE	NS
	NS	PB	PS	PS	NS	NS
	ZE	PS	PS	ZE	NS	NS
	PS	PS	PS	NS	NS	NB
	PB	PS	ZE	NS	NB	NB

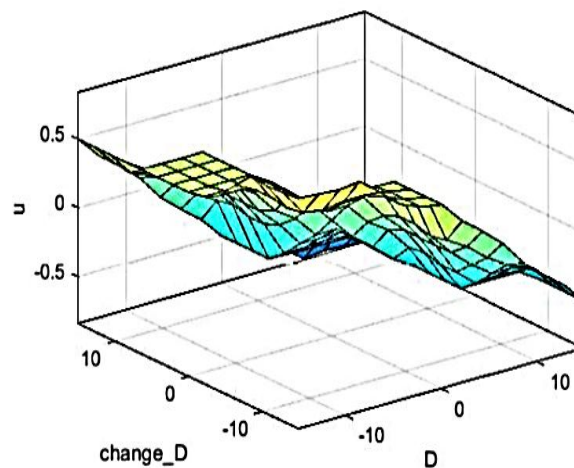


Figure 8. Output surface of the fuzzy logic controller

2.2.4. PI controller

The Proportional-Integral-Derivative (PID) controller is the most common and widely utilized control scheme in the industrial field. It offers advantages such as a simple concept, well-established theory, and clear physical interpretation, making it considered one of the most reliable control solutions in industry. Depending on specific control requirements, different configurations can be employed, such as proportional control, PI control, PD control, or PID control [33]. In this paper, the PI combination is used. The proportional component (P) reduces static error but can negatively affect system stability. The integral component (I) further improves the static error of the plant.

2.2.5. Neutral point voltage balancing

For balancing the neutral point voltage, we use a simple inductive auxiliary circuit. This technique was proposed by [34]. The circuit consists of two switches and an inductor. The inductor facilitates energy transfer between the capacitors until their voltages are balanced. The inductance value is tuned accordingly to ensure smooth energy transfer between the capacitors. Fig. 9 illustrates the described technique.

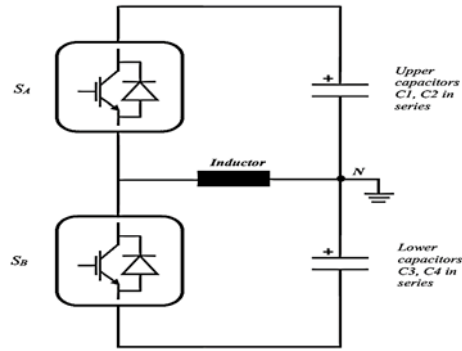


Figure 9. Neutral point voltage balancing

3. RESULTS AND DISCUSSION

Several simulations are conducted in the MATLAB/Simulink virtual laboratory aiming at evaluating the performances of the controllers investigated. The operation of the DC-DC bidirectional converter is assessed in both Boost and Buck modes, and the performance of each controller is analyzed to highlight their strengths and weaknesses. Table 4 presents the simulation parameters of the converter.

The robustness of the proposed controllers is evaluated through tests conducted under three variations of the converter's parameters: changes in the reference voltage, load resistance, and input voltage. In the first two simulations, each lasting 1 second, the reference voltage is set at 8000 V for Boost operation and 475 V for Buck operation. The converter is simulated using four different control strategies: sliding mode controller (SMC), fuzzy sliding mode controller (Fuzzy-SMC), ANFIS sliding mode controller (Anfis-SMC), and PI controller. Figures 10 and 11 present the simulation results for a constant reference voltage.

Table 4. Simulation parameters with their values

Parameters	Designation	Values
V_{in}	DC input source	600V
L_s	Power inductor	200 μ H
m	Transformation ratio	10
f	Frequency	100kHz
$C_1=C_2=C_3=C_4$	DC output capacitor	2500 μ F
C_0	Input capacitor	50000 μ F
R	Load resistance	300 Ω
k_p	Proportional parameter	4.5
k_D	Derivative parameter	4.5

It is evident that all four controllers enable the converter's output to accurately track the reference in both Boost and Buck operations, with the nonlinear controllers demonstrating superior tracking accuracy. The three nonlinear controllers under investigation visually outperform the PI controller in terms of rise time, minimal overshoot, and settling time. Tables 5 and 6 provide a comparative analysis of the controllers' performance metrics—namely, rise time, settling time, overshoot, and static error—in Boost and Buck operations, respectively.

Table 5. Comparative analysis of the converters performances (Boost mode)

	Rise time (ms)	Settling time (ms)	Overshoot (%)	Static error (%)
PI	18.036	269.3	27.174	0.173
SMC	12.989	10.186	0.419	0.449
Fuzzy-SMC	12.988	10.184	0.304	0.525
Anfis-SMC	8.577	19.737	3.137	0.594

Table 6. Comparative analysis of the converters performances (Buck mode)

	Rise time (ms)	Settling time (ms)	Overshoot (%)	Static error (%)
PI	6.376	8.167	1.110	1.380
SMC	1.036	1.196	0.504	1.073
Fuzzy-SMC	1.109	19.961	4.737	1.930
Anfis-SMC	0.986	19.680	1.329	1.994

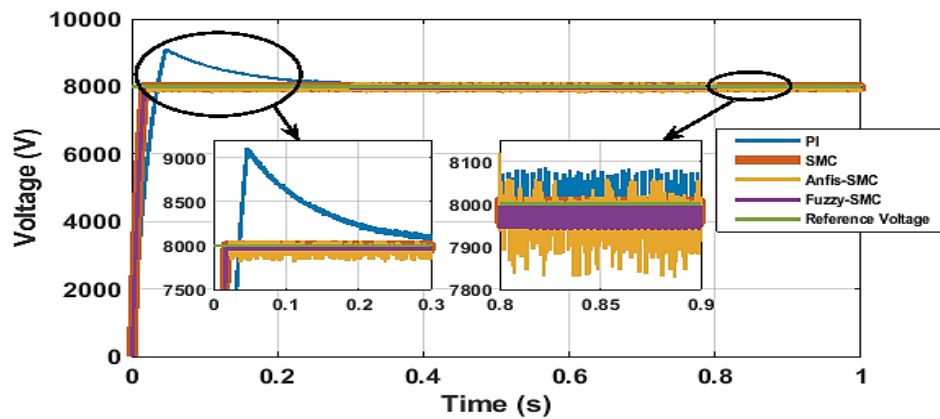


Figure 10. Output response of the converter operating on Boost mode

In terms of rise time, the Anfis-SMC performs better than all the other controllers investigated, with shorter rise times in both Boost and Buck operations (respectively 8.577 ms and 0.986 ms). The SMC and Fuzzy-SMC controllers have shorter settling times in Boost and Buck operations, respectively, unlike the PI controller, whose settling time reaches 269.3 ms in Boost operation. The PI controller exhibits the highest overshoot among all controllers in Boost mode (27.174%), whereas in Buck mode, the Fuzzy-SMC controller shows the highest overshoot.

Regarding static error, the sliding mode controller (SMC) demonstrates the best performance in Buck mode (1.073%), while the PI controller performs best in Boost mode (0.173%). It is also observed that the rise times for the three nonlinear controllers based on sliding mode are very close in Boost operation and in Buck operation, which explains why their responses appear almost superimposed during the rise phase visually. For a better understanding of the controllers' behaviour towards settling time, error graphics are presented for Boost operation (Fig. 12) and for Buck operation (Fig.13); the error being the difference between signal value and reference voltage. Error values towards settling time are close to zero, demonstrating a good tracking of the reference voltage, despite chattering phenomenon which is somewhat important.

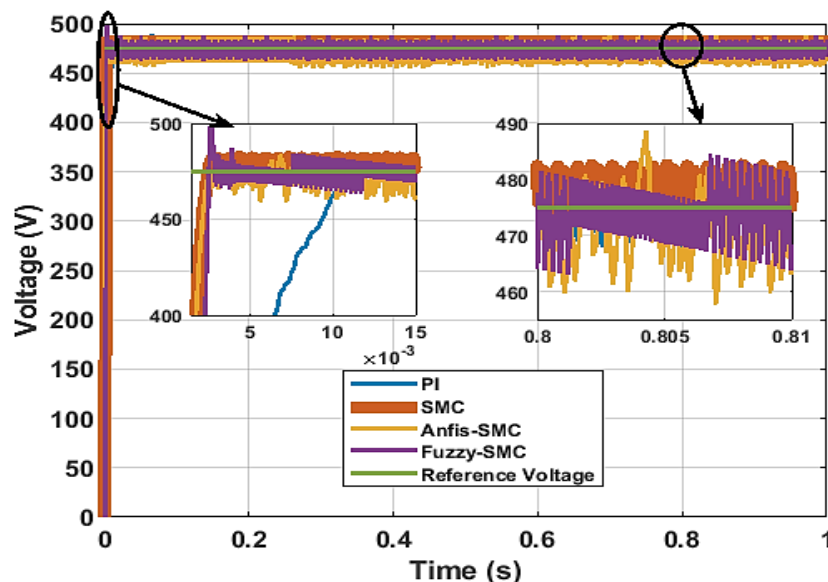


Figure 11. Output response of the converter operating on Buck mode

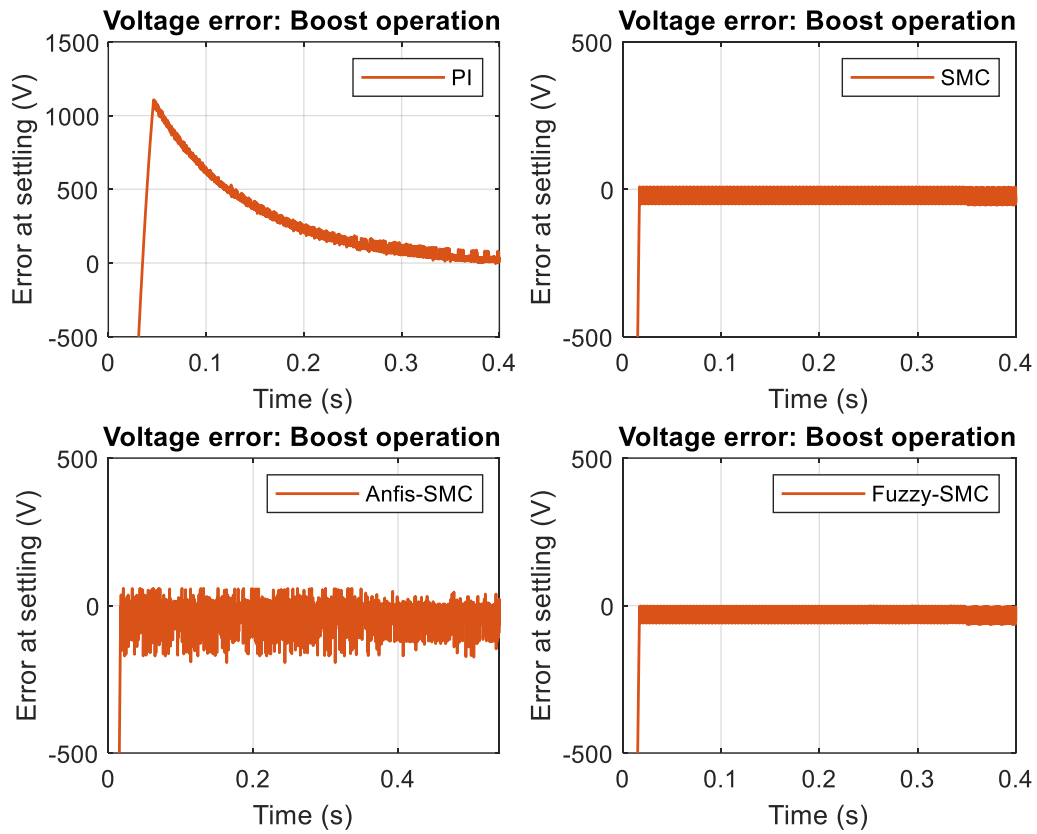


Figure 12. Output voltage error graphics towards settling (Boost operation).

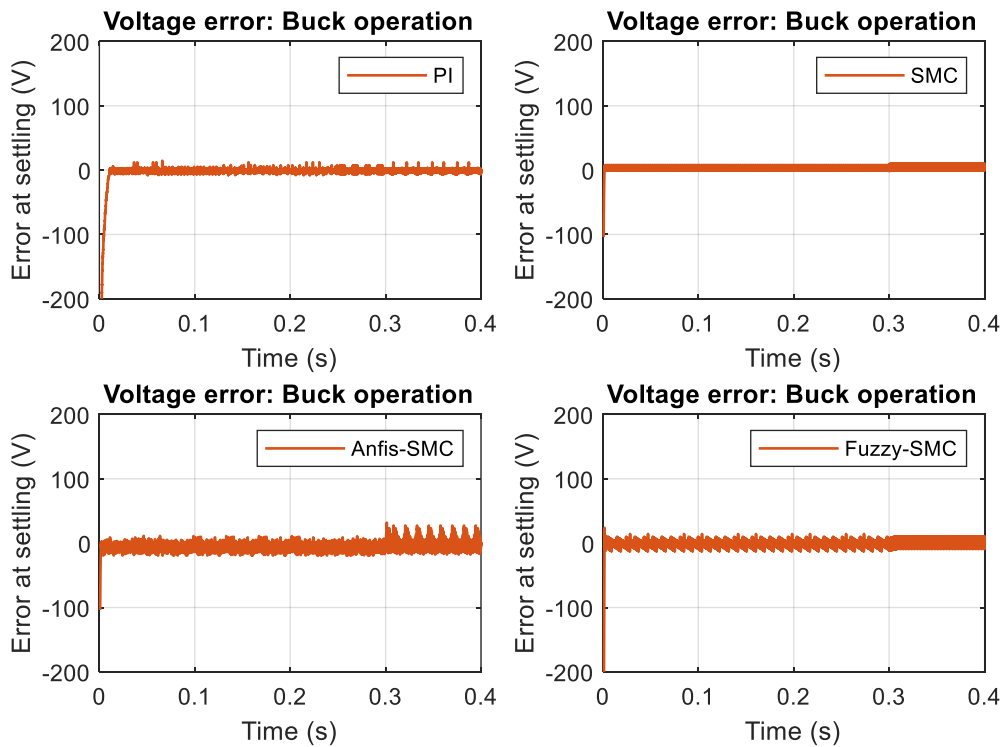


Figure 13. Output voltage error graphics towards settling (Buck operation).

3.1. Robustness test by variation of reference voltage.

In Boost operation, the load resistance is maintained at $1\text{ k}\Omega$ and the input voltage is kept at 600 V . The reference voltage is varied from 6 kV to 8 kV , then from 8 kV to 4 kV at the instants 0.35 s and 0.7 s respectively as depicted by Fig. 14(a).

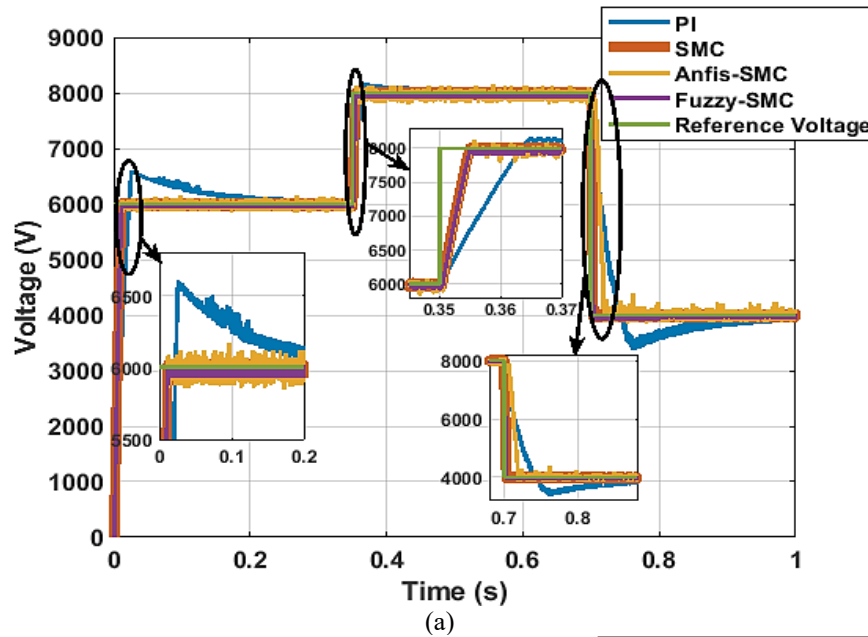
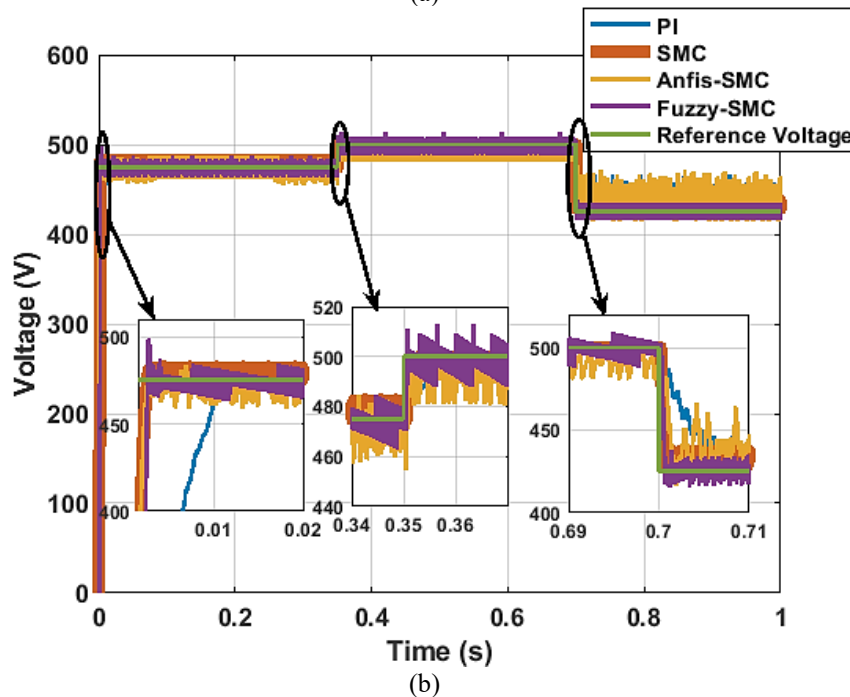


Figure 14. Variation of reference voltage (a. Boost operation, b. Buck operation)

It is observed that in Boost operation, all four controllers exhibit good reference tracking ability. However, the PI controller shows the least attractive dynamic response, with a settling time of 65 ms at the instant 0.3 s and undershoot of nearly 500 V , along with a settling time of about 100 ms at the instant 0.7 s . The SMC and Fuzzy-SMC controllers, on the other hand, demonstrate better dynamic responses during voltage level transitions compared to the Anfis-SMC.

In Buck operation, the load resistance and input voltage are fixed at $1\text{ k}\Omega$ and 10 kV , respectively. The reference voltage varies from 475 V to 500 V at 0.35 s and from 500 V to 425 V at 0.7 s as shown in Fig. 14(b). All four controllers show remarkable voltage tracking capabilities, despite the relatively small variation range (about 100 V). The SMC and Fuzzy-SMC controllers exhibit superior dynamic responses during voltage transitions compared to the Anfis-SMC, with shorter delay times.

3.2. Robustness test by variation of load resistance.

The second robustness test scenario involves load variation. This scenario is very common during the operation of DC-DC converters. In Boost mode, the load resistance varies from 1 k Ω to 0.5 k Ω at 0.35 seconds, and then from 0.5 k Ω to 0.33 k Ω at 0.75 seconds. Fig. 15(a) and Fig. 15(b) depict the load variation scenario for Boost operation and Buck operation of the converter respectively.

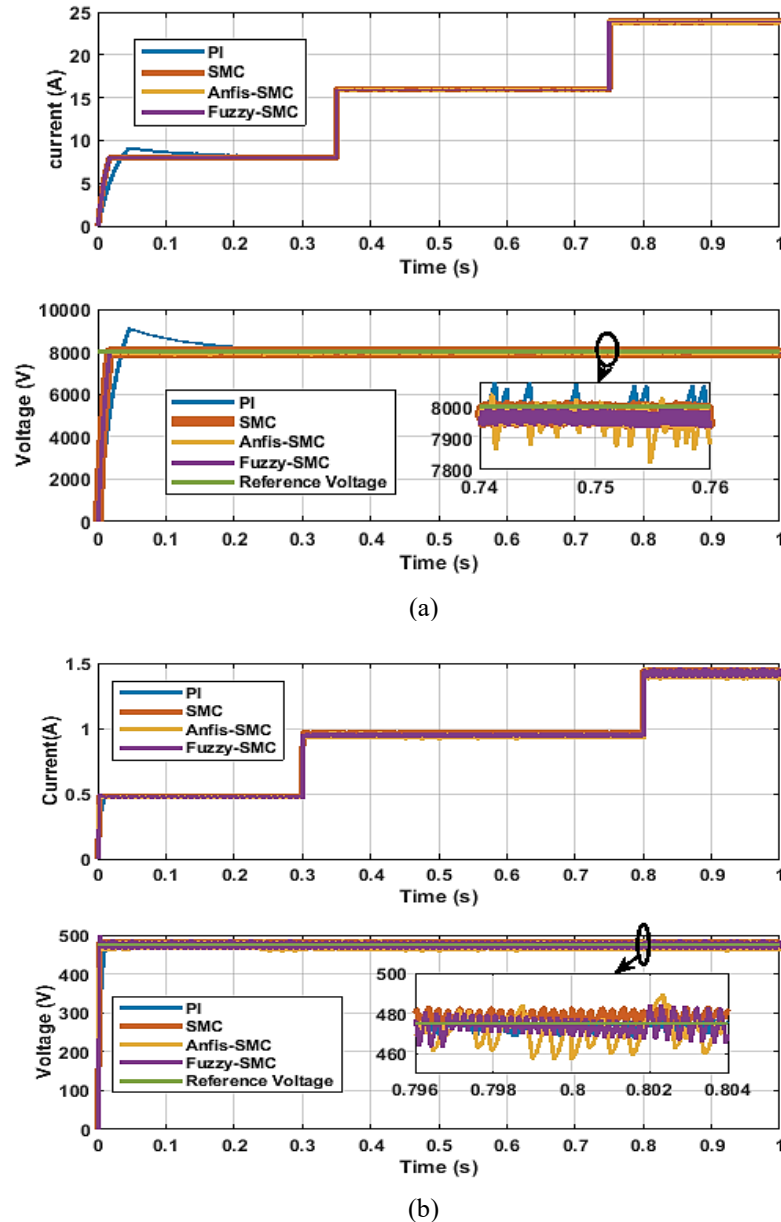


Figure 15. Variation of load resistance (a. Boost operation, b. Buck operation)

It is clearly observed from the simulations in Fig. 15(a) that, despite load variations, the output voltage tracks the set reference of 8 kV for all controllers. Applying a similar scenario in Buck mode, the load resistance varies from 1 k Ω to 0.5 k Ω at 0.3 seconds and from 0.5 k Ω to 0.33 k Ω at 0.8 seconds. As shown in Fig. 15(b), despite significant load variations, the output voltage effectively tracks the set reference of 475 V.

3.3. Robustness test by variation of input voltage.

In Boost mode operation, the input voltage is varied from 500 V to 600 V at 0.3 seconds, and then from 600 V to 400 V at 0.8 seconds, while the load resistance is maintained at 1 k Ω . Despite these variations, the output voltage tracks the set reference of 8 kV, as depicted in Fig. 16(a). Similarly, in Buck mode, the

input voltage varies from 10.5 kV to 11 kV at 0.3 seconds, and then from 11 kV to 10.7 kV at 0.8 seconds, with the load kept at 1 k Ω . The observations show that all four controllers enable the output voltage to follow the set reference of 500 V with remarkable accuracy as shown by Fig 16(b).

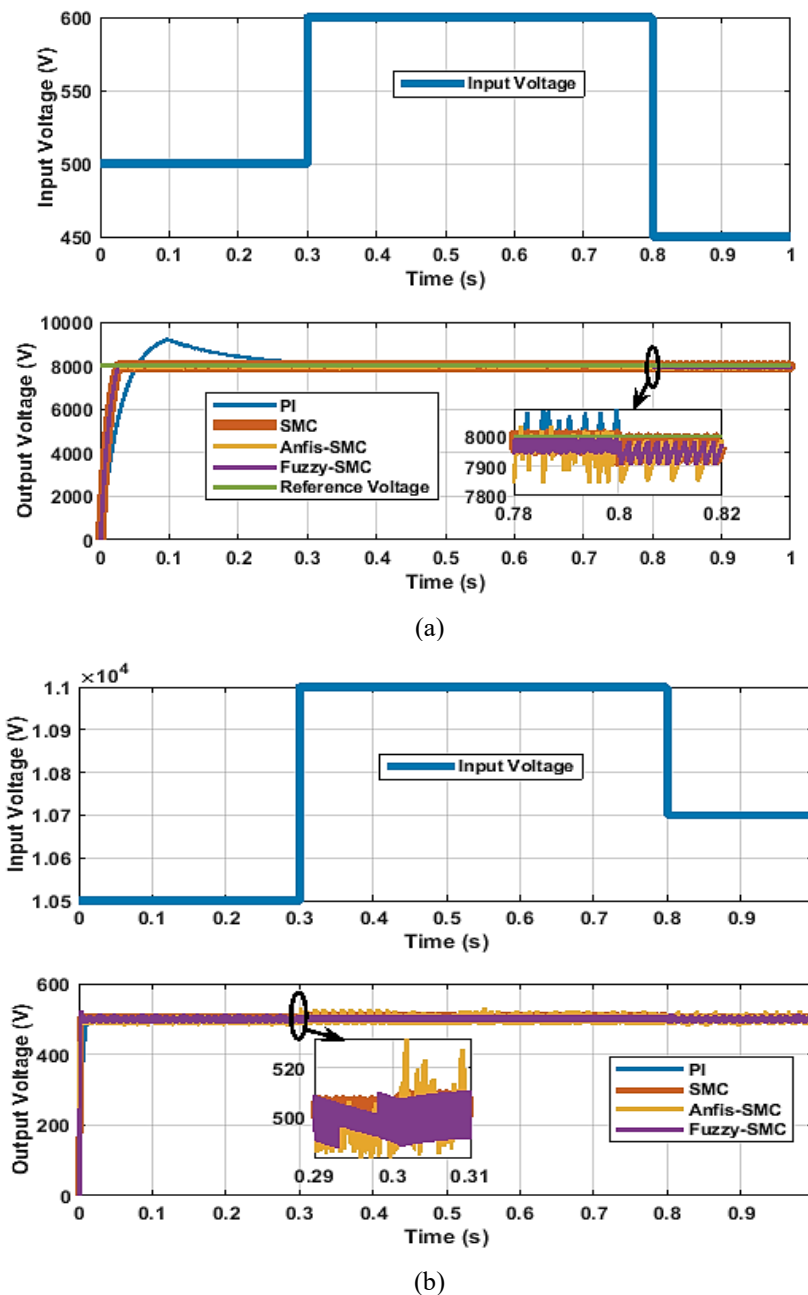


Figure 16. Variation of input voltage (a. Boost operation, b. Buck operation).

3.4. Neutral point voltage balancing.

The voltage at the neutral point is simply the difference between the voltage across the upper capacitors and the voltage across the lower capacitors ($V_n = V_{C12} - V_{C34}$). At steady state, the neutral point voltage is maintained at values close to zero (less than 10^{-6} V), as depicted in Fig.17.

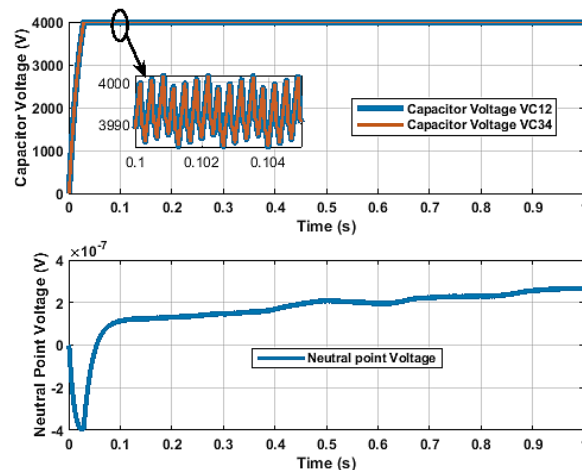


Figure 17. Neutral point voltage balancing

4. CONCLUSION

An investigative study of three sliding mode-related nonlinear controllers (SMC, Anfis-SMC, and Fuzzy-SMC) was proposed in this paper. These controllers were applied to a 3L-NPC based isolated bidirectional DC-DC converter suitable for high-voltage applications. The results of the study revealed that all three nonlinear controllers exhibit strong robustness globally and outperform the classical PI controller. A comparative analysis of the controllers highlights the following key observations: The Anfis-SMC controller demonstrates the best performance in terms of rise time during both Boost and Buck operations of the converter. The Fuzzy-SMC and SMC control algorithms perform best in terms of settling time in Boost mode and Buck mode, respectively. The dynamic performance of all three nonlinear controllers is generally outstanding. The robustness of these controllers was clearly demonstrated through various tests; however, the range of output voltage variation in Buck mode operation is somewhat limited. This presents an opportunity for future research work.

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