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Design of integral sliding mode control and fuzzy adaptive PI control for voltage stability in DC microgrid

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This paper introduces a novel control strategy that merges integral sliding mode control with fuzzy adaptive PI control. This hybrid approach maximizes the benefits of both techniques to ensure voltage stability in DC microgrid. Firstly, a mathematical model characterizes the DC–DC boost converter. Subsequently, a sliding surface, incorporating an integral term, is employed to regulate the converter's output voltage and current errors. To address uncertainties stemming from factors like input inductance and output capacitance, a dynamic sliding mode controller is formulated. The proposed sliding mode control scheme significantly reduces the time required for voltage stability, curbs system oscillations, and showcases robustness. Furthermore, the inclusion of fuzzy adaptive PI control aids in refining the voltage deviation signal and droop resistance. This enhancement improves the precision of the error tracking system. Finally, the effectiveness of this strategy is demonstrated through MATLAB simulations, supported by experimental validation and analysis. The findings reveal that this control strategy efficiently accelerates the convergence of DC microgrid voltage to a stable state.

KEYWORDS

sliding mode control, fuzzy control, adaptive PI control, DC microgrid, voltage stability

1 Introduction

A microgrid can be conceptualized as an integrated power system that encompasses distributed generation systems, loads, and energy storage devices (Ullah et al., 2022). The growing adoption of microgrids is attributed to their heightened reliability, improved economic considerations and reduced global warming impact. The DC microgrid, in particular, has garnered significant attention and research interest in the realm of power engineering owing to its distinct advantages and potential. When contrasted with AC microgrids, DC microgrids offer enhanced reliability, efficiency, and reduced power conversion losses. Additionally, a majority of loads in modern residential and industrial applications are powered by DC sources (Gui et al., 2021; Saafan et al., 2023). Consequently, DC microgrids hold appeal as integral components within contemporary intelligent power systems (Prabhakaran and Agarwal, 2020).

In the current context, with the focal point on sustainable energy and energy efficiency, the significance of DC–DC converters in electrical engineering and microgrid design has gained further prominence (Wang et al., 2020). These converters play a pivotal role in connecting the DC output of renewable energy sources to the distribution system, owing to their cost-effectiveness, straightforward structure, and efficient power conversion performance. This aspect holds vital importance in optimizing energy utilization and enhancing energy efficiency at the user end (Haroun et al., 2015; Tiwary et al., 2023). The fundamental control objectives of a DC microgrid encompass skillful power distribution management and meticulous bus voltage regulation (Li et al., 2021). Prolonged substantial deviations in output voltage can precipitate system instability, necessitating the introduction of stabilizing control methodologies.

Regarding the stability quandary of boost converters, an array of advanced control strategies have been proposed, including proportional resonant (PR) control, proportional integral derivative (PID) control, fuzzy logic-based control, and repetitive control (Zheng et al., 2018). Among these control strategies mentioned above, sliding mode control is considered to be a very efficient nonlinear robust control method due to its large stabilization range, rapid dynamic response, and strong disturbance immunity (Wang et al., 2021; Linares-Flores et al., 2022). In (Liu et al., 2011), the authors designed two control loops containing different converters which involve variable charging and discharging modes to enhance the productivity of a hybrid power system. The designed method, although it has improved the efficiency of the system, employs electrical components such as bi-directional converters and inductors that are too idealized and do not take into account the presence of uncertainties at the same time, which does not achieve a fast tracking of the errors. Literature (Mao et al., 2022) tries to solve this problem by incorporating T-S fuzzy control when dealing with nonlinear state variables, so as to improve the utilization of PV cells connected to the microgrid while maintaining the stability of the bus voltage, but the procedure is relatively time consuming. The maintenance of system stability is an important task in control theory. In traditional discontinuous control theory, the generation of control rates usually relies on sign functions or hysteresis modulators and in this way ensures the stability of the system. These generated control laws must satisfy certain specific inequality conditions (Biricik and Komurcugil, 2016; Merabet et al., 2017) to ensure their validity. However, a noteworthy issue is that this control strategy still suffers from output chattering. This may negatively affect the system performance, especially in applications with high precision control or high dynamic response. To address this issue, researchers have started to consider the use of smoothing control law to eliminate the vibration problem of discrete-time sliding mode control. This is an effective strategy, which can suppress the chattering to a certain extent and thus improve the system performance. However, the smoothing control law is not without problems. The primary problem is that this control method may limit the regulation capability and dynamic response of the converter. Literature (Inomoto et al., 2022) provides a solution to the above problem by designing two control loops in the sliding mode controller. The first is an input voltage control loop for computing the inductive current, guided by the MPPT algorithm. The second circuit controls the current, which is related to the duty cycle of the switches. These two loops enhance the performance of the converter. The proposed technique uses a smooth switching function to avoid chattering, resulting in a substantial shortening of the time to reach a steady state. However, the literature selects high-order sliding surfaces, which leads to the drawback of overly complex algorithmic calculations.

The means for treating system uncertainties and variations are not only sliding mode control, the adaptive PI control and fuzzy control are also often in the priority list. Literature (Mi et al., 2019) incorporates a T-S fuzzy model in a sliding mode controller designed for the DC microgrid. Since the relationship between the output voltage and power of distributed power sources is nonlinear, the T-S fuzzy model is introduced for processing. The sliding mode droop control is used to improve the vibration resistance of the system due to parameter uncertainties and variations in operating conditions. This combination enables the system to be more accurate when allocating power according to the load. In the literature (Ahmed et al., 2018), the author addresses the occurrence of phenomena such as short-circuits or abrupt changes in load during the operation of power electronic devices. A fuzzy logic control was integrated into the coefficients of traditional PI controllers, enabling the controller to rapidly respond to these changes. Taking power electronic distribution transformer as an example, the voltage and current errors are transferred to the improved PI controller and the performance of the controller in its application under different operating conditions is considered. The experiment demonstrates that the proposed controller is capable of meeting the desired requirements, but suffers from the problem of slow response time. The authors in (Mokhtar et al., 2019) employed a sliding mode controller to control the tracking error, and then added an adaptive PI controller to adjust the error-related voltage and current more accurately, but the sliding mode control portion of it was not sufficiently stable for voltage error control. Different from the previous work that only considered different control methods combined together, in the literature (Jan et al., 2020), the authors emphasized on the improvement of the parameters while applying two control methods, in which the parameters are inferred by using the affiliation function and fuzzy rule table, and genetic algorithms are also involved. Ultimately, the output power of the renewable energy source can be maximized, while these measures assure the frequency stabilization in the system. However, with this control method, unknown system parameters need to be estimated through the use of multiple adaptive laws, which leads to the over-parameterization problem. Literature (Kuppusamy and Joo, 2021) designed a memory-integrated sliding mode control based on perturbation observer using T-S fuzzy approach, which defines an integral fuzzy switching surface function containing both input matrix and implicit parameters related to the state variables, and utilizes the disturbance estimation generated by the perturbation observer to offset the mismatched disturbance error. This strategy has a T-S fuzzy modeling of the sliding mode motion, which operates according to the control model in the initial state and maintains this state continuously under the limitations of the memory sliding mode. This method is guaranteed for the fast response of the system while preserving its continuous stability.

Addressing the challenge posed by the complex and uncertain operational environment, which impedes the maintenance of a sustained steady state, this study introduces a novel sliding mode control (SMC) scheme. To secure the stable operation of the DC microgrid, an integral sliding surface is constructed, subsequently refining the traditional SMC approach. The stability of the improved SMC method is substantiated through an appropriate Lyapunov function.

The main contributions of this paper are as follows.

1) The proposed SMC effectively mitigates system chattering by incorporating an integral sliding surface design, markedly enhancing tracking performance and ensuring voltage stability;

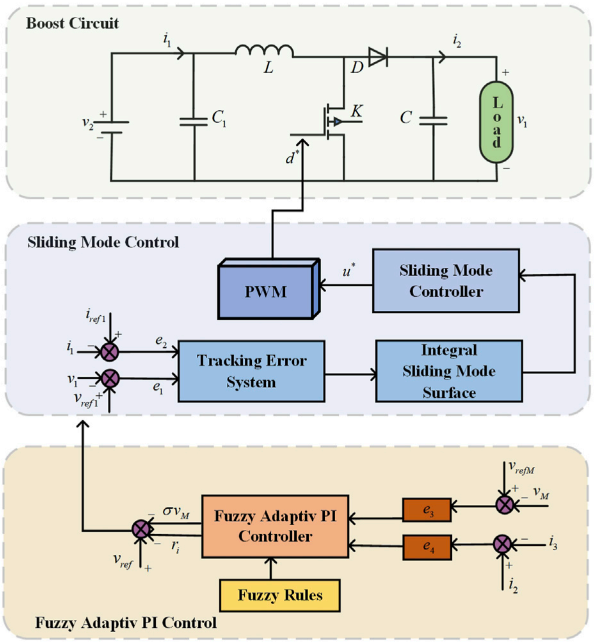

FIGURE 1
The general framework of the proposal control strategy in the DC microgrid.

2) An adaptive PI controller is combined to govern the error between the DC bus voltage and its reference value and the droop resistance to optimize voltage regulation. This combination yields a more precise converter output voltage;
3) Parameter tuning for the adaptive PI controller leverages fuzzy rules, allowing adaptation to varying internal and external parameters.

The rest of this paper is organized as follows. Section 2 shows the system model of the DC–DC converter. Section 3 introduces the designed sliding mode controller. Section 4 describes the fuzzy adaptive PI control. Section 5 presents the simulation results. The conclusion is illustrated in Section 6.

2 System model of the DC–DC converter

DC–DC converters are utilized in numerous applications in power systems. These converters manipulate the power electronics' on/off states to modulate current transmission paths for voltage augmentation. Notably, boost converters offer distinct advantages across diverse scenarios. Their short duty cycles translate to comparatively low energy losses, a crucial attribute for extended-operation devices like remote communication systems, computers, and office automation equipment. Moreover, boost converters find favor in precision-demanding sectors like military and aerospace owing to their stable output voltage traits (Lee et al., 2011). In essence, the realm of DC–DC converters is characterized by diversity and multifold applications, encompassing varied types. Boost converters, specifically, have seamlessly integrated into myriad domains owing to their distinctive attributes. Figure 1 illustrates the overarching framework of the described control strategy. The mathematical representation of a DC–DC converter is given by

$$\begin{cases} \frac{dv_1}{dt} = \frac{-i_2}{C} + \frac{-(u-1)i_1}{C} \\ \frac{di_1}{dt} = \frac{v_2}{L} + \frac{(u-1)v_1}{L} \end{cases} \tag{1}$$

where v_1 is the actual output voltage of the converter, v_2 is the input supply voltage of the converter, i_1 is the inductor current, i_2 is the actual output current, and u is the switching state, $u \in [0, 1]$.

3 Proposed sliding mode control

In microgrids, whether the voltage is stable or not is of especially significance for improving the performance of control accuracy and response speed, including ensuring the stable operation of microgrids. For this reason, the control approach used in this paper is the sliding mode control, where the object of control is chosen to be a tracking error system consisting of errors in output voltage and inductive current with their reference values, we introduce the following definitions:

$$e_1 = v_{ref1} - v_1 \tag{2}$$

where v_{ref1} is the reference value of the converter output voltage, and e_1 is the error between the output voltage and the reference value of the output voltage.

$$e_2 = i_{ref1} - i_1 \tag{3}$$

where i_{ref1} is the reference value of the converter output current, e_2 is the error between the converter output current and the current reference value. e_1 and e_2 are the tracking error state variables. From this, the dynamic equation for the tracking error of the system could be given in the following formulation:

$$\dot{e} = Ae + Bx(t)u + D(t) \tag{4}$$

In Eq. 4, the system state matrices e, A, B, $x(t)$ and $D(t)$ can be express by

$$e = \begin{bmatrix} e_1 & e_2 \end{bmatrix}^T$$

$$A = \begin{bmatrix} 0 & \frac{1}{C} \\ \frac{-1}{L} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{C} & 0 \\ 0 & \frac{-1}{L} \end{bmatrix}$$

$$x(t) = \begin{bmatrix} i_1 & v_1 \end{bmatrix}^T$$

$$D(t) = \begin{bmatrix} \frac{i_2 - i_{ref1}}{C} & \frac{v_{ref1} - v_2}{L} \end{bmatrix}^T$$

The design of the sliding surface is crucial and it directly determines the dynamic properties of the system under sliding mode motion. After the system state reaches the sliding surface, the behavior will be governed by the nature of the sliding surface. This means that the system is robust to parameter variations and external perturbations. However, the traditional sliding mode control can lead to a large chattering in the system due to the high frequency switching characteristics of the sliding surface. Hence, during the refinement of the algorithm, a consideration of how to balance the robustness in the system with the need to suppress chattering is warranted to gain an optimization of the control capability of the converter. The introduction of an integral term into the sliding surface is a mean to attenuate the high-frequency switching and consequently reduce the system vibration to a certain extent. The integral sliding surface can ensure more stable system operation. Therefore, the following sliding surface containing integral term is selected.

$$s = g_1 e + g_2 \int_0^t e dt \tag{5}$$

where g_1 and g_2 are constant matrices, $g_1 = [\, g_{11} \;\; g_{12} \,]$, $g_2 = [\, g_{21} \;\; g_{22} \,]$, g_{11}, g_{12}, g_{21} and g_{22} are constants, respectively.

Substituting Eq. 4 into the derivative of the integral sliding surface (5) yields

$$\dot{s} = g_1 (Ae + Bx(t)u + D(t)) + g_2 e \tag{6}$$

The equivalent control law can be obtained by setting Eq. 6 to be zero

$$u_{eq} = -(g_1 Bx(t))^{-1} [(g_1 A + g_2)e + g_1 D(t)] \tag{7}$$

Taking parameter uncertainty and resistance to perturbations into account as well, the hyperbolic tangent function is adopted and the final design of the sliding mode controller is expressed as follows:

$$\begin{aligned} u^* = &-(g_1 Bx(t))^{-1} [(g_1 A + g_2)e + g_1 D(t)] \\ &+(g_1 Bx(t))^{-1} \Big(-\eta \sqrt{|s|}\, sgn(s) - \int_0^t \tau sgn(s) dt \\ &-\lambda tanh(s) - \theta sgn(s) \Big) \end{aligned} \tag{8}$$

where η, τ and θ are normal numbers, λ is a negative real number, and $|\lambda| \le \theta$, $sgn(s)$ are sign functions.

In this improved sliding mode controller, $\eta\sqrt{|s|}sgn(s)$, $\int_0^t \tau sgn(s)dt$ and $\theta sgn(s)$ are used to resist disturbances and reduce chattering. The purpose of adding $\lambda tanh(s)$ is to speed up the convergence of the system. The condition $|\lambda| \le \theta$ is to ensure system stability.

In order to analyze the stability of the proposed sliding mode control, the following Lyapunov function is selected.

$$V = \frac{1}{2}s^2 \tag{9}$$

Differentiating the Lyapunov function and combining with Eq. 8, it yields

$$\begin{aligned} \dot{V} &= s\dot{s} \\ &= s[g_1 A(e + Bx(t)u + D(t)) + g_2 e] \\ &= s\{g_1 [Ae + Bx(t)\big(-(g_1 Bx(t))^{-1} [(g_1 A + g_2)e + g_1 D(t)] \\ &\quad +(g_1 Bx(t))^{-1} (-\eta\sqrt{|s|}sgn(s) - \int_0^t \tau sgn(s)dt \\ &\quad -\lambda tanh(s) - \theta sgn(s))\big) + D(t)] + g_2 e\} \\ &= s\big(-\eta\sqrt{|s|}\, sgn(s) - \textstyle\int_0^t \tau sgn(s)dt - \lambda tanh(s) - \theta sgn(s)\big) \\ &= -\eta\sqrt{|s|}|s| - \tau s \textstyle\int_0^t sgn(s)dt - \lambda s tanh(s) - \theta|s| \le 0 \end{aligned} \tag{10}$$

The above-mentioned verification indicates that the derivative of the Lyapunov function $\dot{V} \le 0$, affirming the stability of the controller devised in this study.

In a high switching frequency environment, the duty cycle can be interpreted as a smooth analytic function of the discrete pulses in a pulse width modulation (PWM) control system. The duty cycle of the DC–DC boost converter is a key parameter that determines the adjustment range and stability of the output voltage. The average control motion of the sliding mode control system can theoretically be viewed as the average dynamic response of a PWM control system. However, regardless of the output of the SMC system, the actual physical meaning has a limitation on the value of the duty cycle, which must be in the region of [0, 1]. Therefore, we can design an actual duty cycle d^* for generating a PWM control signal to drive the controllable switches of the converter. In this study, we use PWM to generate pulse signals to control the converter switches by opening and closing them, thus realizing the precise regulation of the system. The actual duty cycle d^* is expressed as follows:

$$d^* = \begin{cases} 1 & d \ge 1 \\ -(g_1 Bx(t))^{-1} [(g_1 A + g_2)e + g_1 D(t)] & \\ +(g_1 Bx(t))^{-1} (-\eta\sqrt{|s|}\, sgn(s) - \int_0^t \tau sgn(s)dt & 0 < d < 1 \\ -\lambda tanh(s) - \theta sgn(s)) & \\ 0 & d \le 0 \end{cases} \tag{11}$$

4 Fuzzy adaptive PI control

To make the voltage error more accurate and ensure enhanced stability in the output voltage of the converter, two fuzzy adaptive PI controllers are added to the treatment of the voltage tracking error. These controllers serve to enhance precision in managing the DC bus voltage and the droop resistance, respectively. The inputs of adaptive PI controllers are the DC bus voltage error and the current distribution error. By manipulating the droop control parameters, precise control over the current allocation for each distributed generation system within the microgrid is achieved, leading to elevated power quality and microgrid reliability. The following equation presents an adaptive droop system expression:

$$v_{ref1} = v_{ref} + \sigma v_M - r_d i_2 \tag{12}$$

where σv_M is the voltage deviation signal to regulate the DC bus voltage v_M and its reference value v_{ref}, r_d is the droop resistance of the converter. The voltage deviation signal can be expressed by

$$\sigma v_M = -q_1 q_{2p}(t) e_3(t) + q_1 \int_0^t q_{3i}(t) e_3(t) dt \tag{13}$$

$$e_3(t) = v_{refM} - v_M \tag{14}$$

where $e_3(t)$ is the difference between the DC bus voltage v_M and its reference value v_{refM}, q_1 is a positive constant, $q_{2p}(t)$ is a proportional gain coefficient, and $q_{3i}(t)$ is an integral gain coefficient. The proportional and integral gains are expressed as follows:

$$q_{2p}(t) = e_3{}^2(t) + \rho_1 \int_0^t e_3{}^2(t) dt \tag{15}$$

$$q_{3i}(t) = \rho_2 \int_0^t e_3{}^2(t) dt \tag{16}$$

where ρ_1 and ρ_2 are normal numbers.

In the practical operation of microgrids, due to the occurrence of sudden changes in loads, etc., the currents are not immune to additional errors, which can have an effect on the droop resistance in the droop system. We have to cope with this situation and the new droop resistance can be written by

$$r_i = -q_4 q_{5p}(t) e_4(t) + q_4 \int_0^t q_{6i}(t) e_4(t) dt + r_d \tag{17}$$

$$q_{5p}(t) = {e_4}^2(t) + \rho_3 \int_0^t {e_4}^2(t) dt \tag{18}$$

$$q_{6i}(t) = \rho_4 \int_0^t {e_4}^2(t) dt \tag{19}$$

$$e_4(t) = i_2 - i_3 \tag{20}$$

where r_i is the new droop resistance, $e_4(t)$ is the current distribution error between actual output current and expected current, i_3 is the current expected value, q_4 is a constant, $q_{5p}(t)$ and $q_{6i}(t)$ are the proportional and integral gain coefficients in the current distribution loop, respectively, ρ_3 and ρ_4 are normal numbers.

While the conventional PI control approach enjoys widespread application, it exhibits poor robustness, susceptibility to voltage overshoot and current surges, and sensitivity to alterations in system parameters and nonlinear traits. Fuzzy control, in contrast, is an adaptable method not contingent upon an accurate system model. It showcases robustness, particularly when handling nonlinear systems. Nonetheless, despite the merits of fuzzy control, its performance might lag behind that of conventional PI control in certain instances. To synergize the advantages of both approaches and surmount their individual limitations, this paper combines fuzzy control with an adaptive PI controller. This combination enables online self-adjustment of PI parameters through fuzzy rules to make the parameters more accurate and flexible. The method seamlessly combines the robustness of fuzzy logic and the intuition of PI control, enabling the controller to flexibly adapt to diverse load variations and voltage fluctuations. Specifically, the engineered fuzzy adaptive PI controller initially acquires system error and error variation rate data. Subsequently, it employs a fuzzy logic system to conduct reasoning based on this information, adjusting parameters based on the outcomes. This design empowers the controller to dynamically fine-tune its performance to accommodate shifts in the system state.

The fuzzy domains of the fuzzy input variables e_3 and Δe_3 are set to [−6, +6], and the fuzzy domains of the fuzzy controller outputs $\Delta q_{2p}(t)$ and $\Delta q_{3i}(t)$ are set to [−6, +6] respectively. The membership functions are defined as NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big). Based on the experience of previous engineers and repeated experiments, fuzzy rule control tables are shown in Table 1 and Table 2. Subsequently, the membership function is determined, considering the degree of coverage of the domain and robustness, stability and sensitivity, the linguistic values of the fuzzy linguistic variables in this paper are using the triangular membership function, as shown in Figure 2.

TABLE 1 Fuzzy rule control table of $\Delta q_{2p}(t)$ and $\Delta q_{5p}(t)$

e	Δ*e*						
	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	NB	PM	PS	PS	ZE
NM	PB	PB	NM	PM	PS	ZE	ZE
NS	PB	PM	NS	PS	ZE	NS	NM
ZE	PM	PM	ZE	ZE	NS	NM	NM
PS	PM	PS	ZE	NS	NS	NM	NM
PM	PS	ZE	NM	NM	NM	NB	NB
PB	ZE	NM	NS	NM	NB	NB	NB

TABLE 2 Fuzzy rule control table of $\Delta q_{3i}(t)$ and $\Delta q_{6i}(t)$

e	Δ*e*						
	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	ZE	NB	NM	NM	PS	PS
NM	ZE	ZE	NM	NM	NS	ZE	ZE
NS	ZE	ZE	NS	NS	ZE	ZE	ZE
ZE	ZE	ZE	NS	NM	PS	ZE	ZE
PS	ZE	ZE	ZE	PS	PS	ZE	ZE
PM	ZE	ZE	PS	PM	PM	ZE	ZE
PB	NS	NS	NS	PM	PB	ZE	ZE

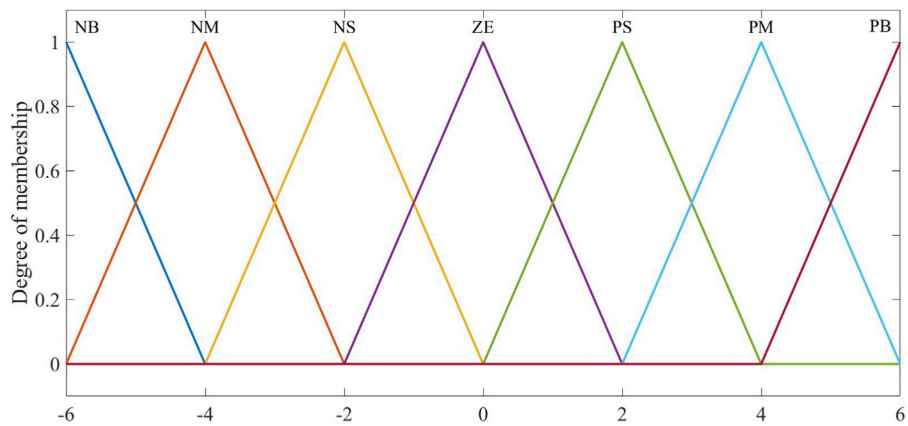

FIGURE 2
The membership function.

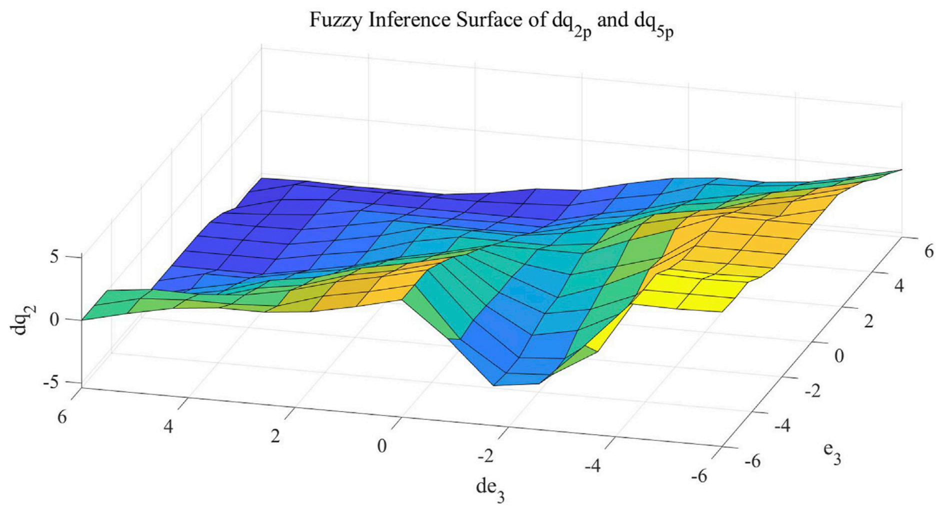

FIGURE 3
Fuzzy inference surface of $\Delta q_{2p}(t)$ and $\Delta q_{5p}(t)$.

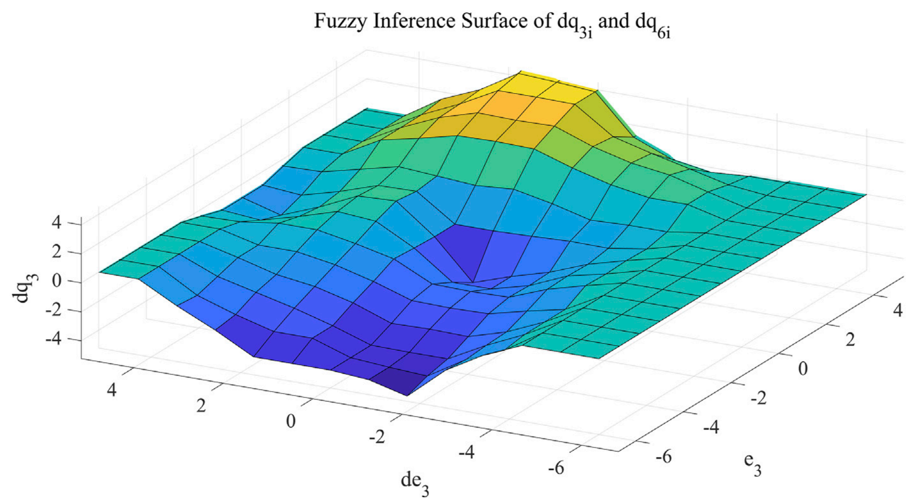

FIGURE 4
Fuzzy inference surface of $\Delta q_{3i}(t)$ and $\Delta q_{6i}(t)$.

Finally, the new scale and integration coefficients are obtained. Figure 3 and Figure 4 illustrate the fuzzy inference surface after the fuzzy rule.

The improved adaptive parameters are expressed as follows:

$$\begin{cases} q_{2p}^{*}(t) = q_{2p}(t) + \Delta q_{2p}(t) \\ q_{3i}^{*}(t) = q_{3i}(t) + \Delta q_{3i}(t) \end{cases} \tag{21}$$

where $q_{2p}{}^{*}(t)$ and $q_{3i}{}^{*}(t)$ are the new proportional and integral gain coefficients, $\Delta q_{2p}(t)$ and $\Delta q_{3i}(t)$ are the fuzzy controller output values respectively.

According to the same principle, the coefficients of the second fuzzy adaptive PI controller can be obtained as follows:

$$\begin{cases} q_{5p}^{*}(t) = q_{5p}(t) + \Delta q_{5p}(t) \\ q_{6i}^{*}(t) = q_{6i}(t) + \Delta q_{6i}(t) \end{cases} \tag{22}$$

where $q_{5p}^{*}(t)$ and $q_{6i}^{*}(t)$ are the new proportional and integral gain coefficients, $\Delta q_{5p}(t)$ and $\Delta q_{6i}(t)$ are the fuzzy controller output values respectively.

TABLE 3 System parameters.

Parameters	Value	Parameters	Value
L	100μH	τ	0.3
C	100μF	λ	−0.35
r_d	1Ω	θ	0.4
v_{ref1}	48V	q_1	4.5
i_{ref1}	1A	ρ_1	0.01
g_{11}	0.1	ρ_2	0.1
g_{12}, g_{22}	0.15	q_4	10
g_{21}	8	ρ_3	10
η	1.45	ρ_4	9

5 Simulation results

This subsection aims to substantiate the efficacy of the proposed algorithm through simulation examples. The parameters involved in the simulation are shown in Table 3.

Initially, we excluded the influence of external disturbances and solely evaluated the control performance of the proposed method under ideal circumstances. A comparison with the traditional SMC approach yielded the subsequent simulation outcomes. Referring to Figure 5 and Figure 6, we deduce that, within the confines of the control strategy, the system rapidly and effectively attains the desired target value. Notably, the proposed method exhibits a briefer regulation duration and significantly reduced chattering compared to the conventional method. In addition, the traditional SMC cannot accurately achieve the reference value of voltage. Upon examining Figure 5 and

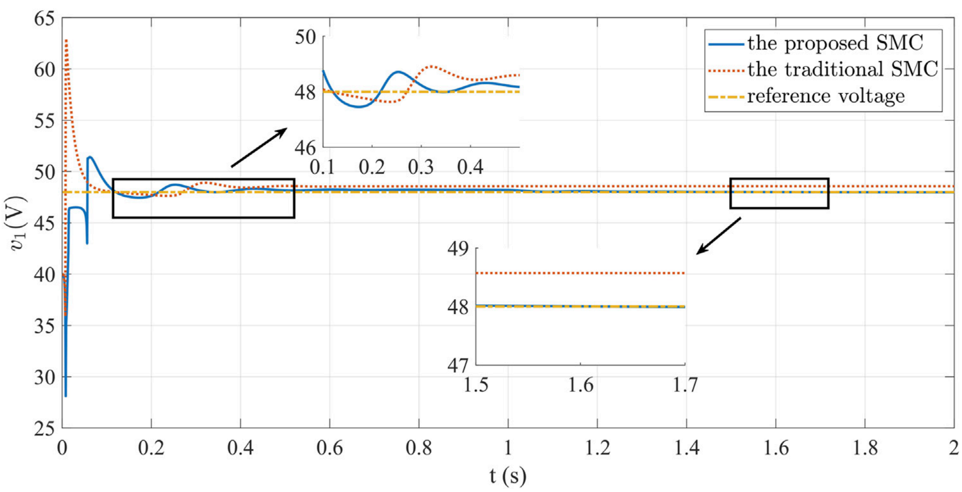

FIGURE 5
Curves of converter output voltage under ideal circumstances.

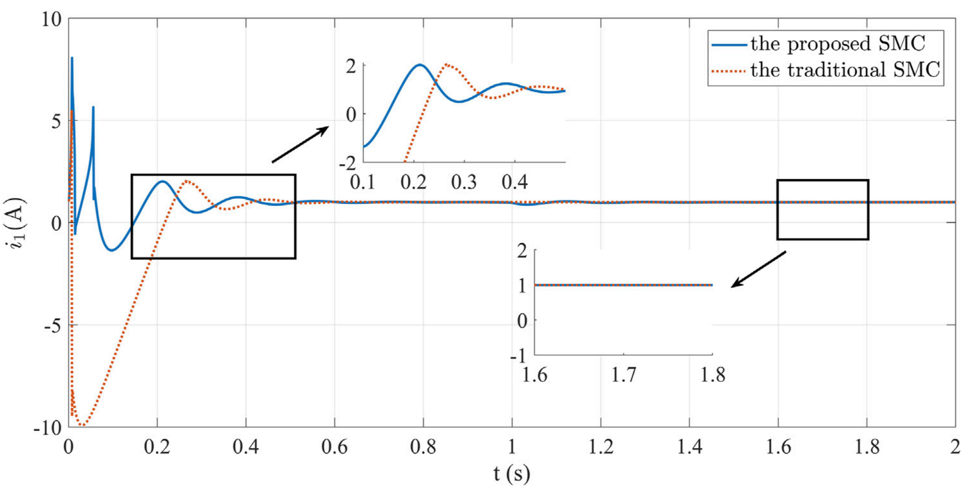

FIGURE 6
Curves of converter inductive current under ideal circumstances.

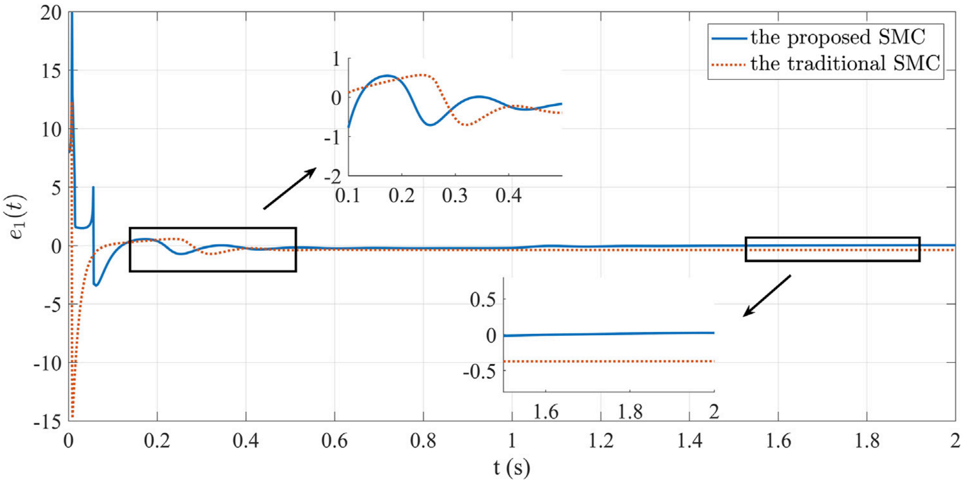

FIGURE 7
Curves of voltage error in the DC–DC converter under ideal circumstances.

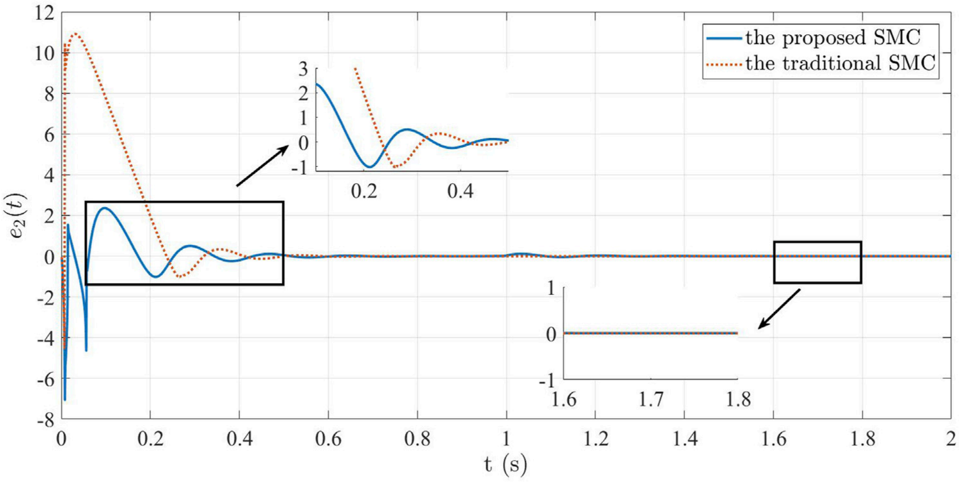

FIGURE 8
Curves of current error in the DC–DC converter under ideal circumstances.

Figure 7 concurrently, it becomes evident that the traditional method fails to achieve the desired voltage value, perpetuating an enduring error. The data in Figure 8 highlights the exceptional current control capability of the strategy developed in this paper. The current error swiftly converges to be zero within a brief span, and the oscillation amplitude remains notably smaller in comparison to the traditional method. Under ideal conditions, the advanced controller advocated in this study vividly showcases its prowess in dynamic performance enhancement.

To emulate real power system conditions, scenarios involving external disturbances were examined. Load variations were tested and discussed across different cases, with a comparison made to the performance of the traditional SMC method in these conditions. The ensuing simulation findings are presented as follows. Analyzing Figure 9, we infer that when external interference is present, the system tracks the predefined reference value quickly and effectively after changing the load, achieving regulation within 0.1 s. Figure 9 highlights that sizeable external disturbances induce more pronounced voltage fluctuations and changes under traditional SMC. This observation underscores the traditional method's inferior robustness and diminished anti-interference capacity. In contrast, the control strategy proposed herein swiftly stabilizes the system's output voltage, rapidly restoring equilibrium post-referential attainment. This exemplifies the strategy's enhanced robustness and its capacity to suppress the influence of external

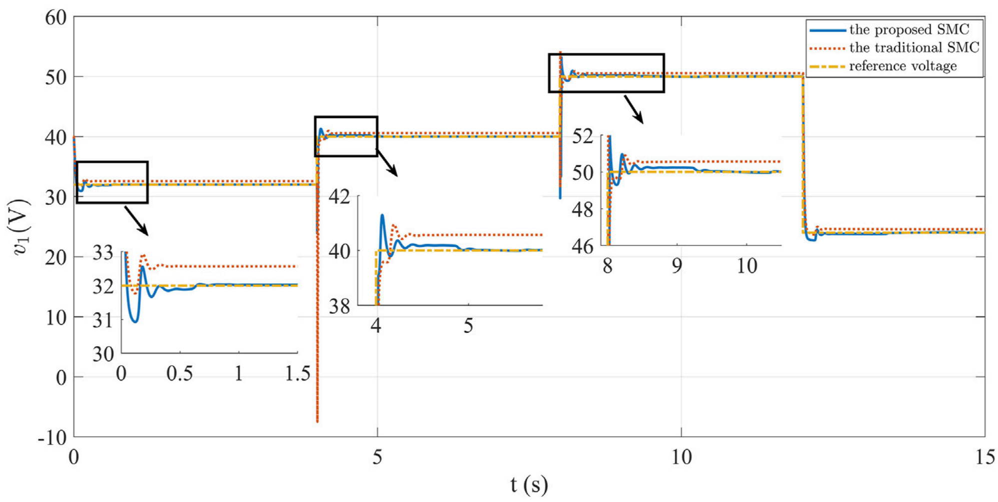

FIGURE 9
Dynamic curves of converter output voltage.

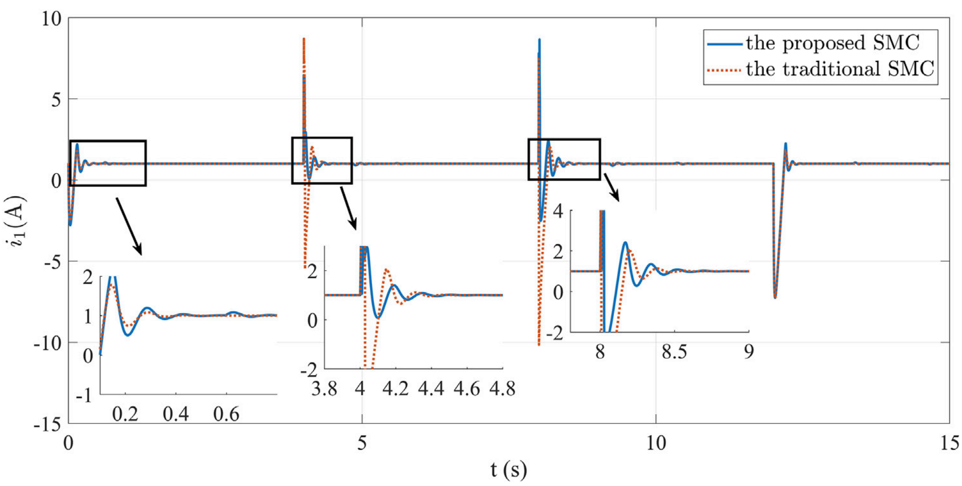

FIGURE 10
Dynamic curves of converter inductive current.

disturbances, thereby effectually advancing system control. Figure 10 presents the current variation. Although both methods can achieve the set reference value, the proposed method restrains the chattering. Figure 11 visually illustrates the voltage error, manifesting the error's eventual convergence to be zero under the controller's influence. This outcome underscores the effective asymptotic tracking capability of the current control strategy. In contrast, traditional SMC fail to converge the voltage error to be zero. Figure 12 illustrates current tracking error evolution. Notably, the traditional SMC method exhibits substantial performance deviations when faced with external disturbances. The proposed SMC enables the current error to reach the convergence state more quickly and steadily.

The simulation outcomes decisively showcase the proposed controller's pronounced improvements in both response time and precision, when juxtaposed with the conventional sliding mode controller. This method streamlines the algorithm, enhances voltage stability control, and optimizes overall system performance. These results affirm the effectiveness and superiority inherent in combining SMC and fuzzy adaptive PI control within DC–DC boost converter control.

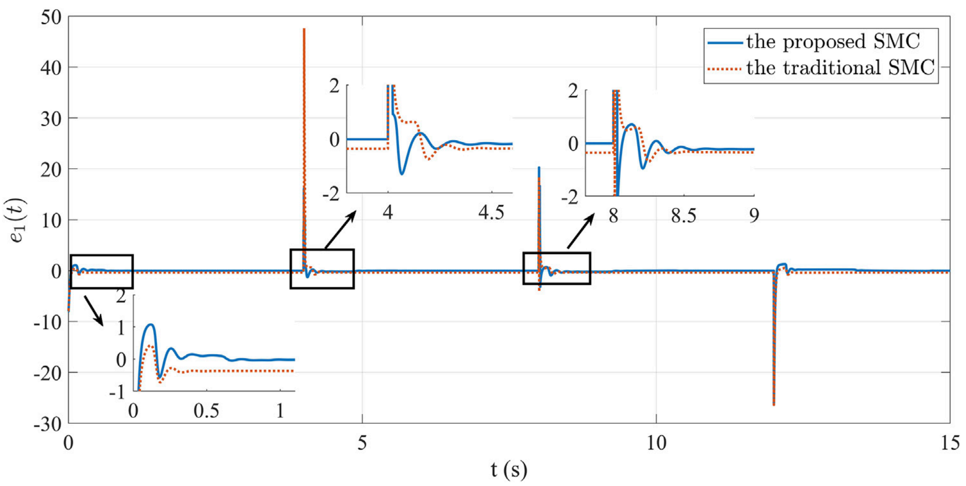

FIGURE 11
Curves of voltage error in the DC–DC converter.

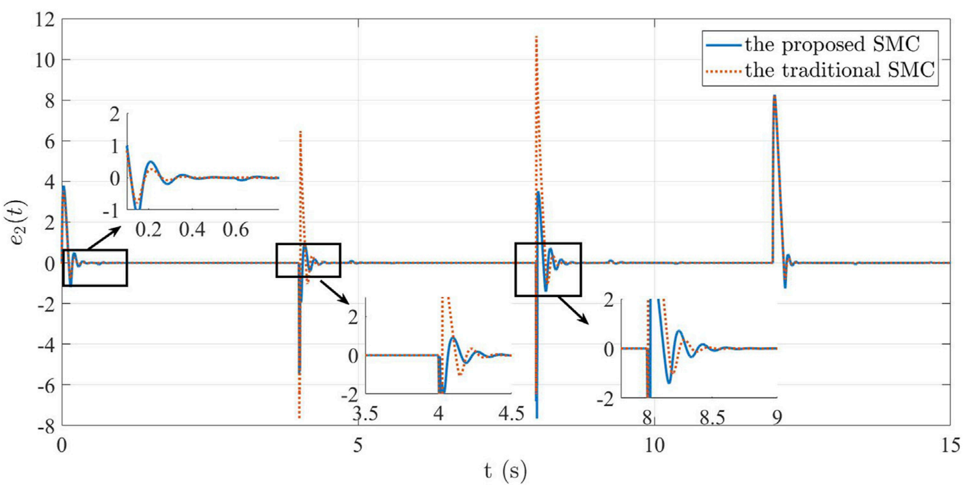

FIGURE 12
Curves of current error in the DC–DC converter.

6 Conclusion

This study proposes a voltage stabilization control strategy for DC–DC converters within DC microgrids, employing integral SMC and fuzzy adaptive PI control. The strategy effectively addresses the challenge of achieving rapid and steady output voltage states. The primary aim is to enhance dynamic performance and attain exceptional tracking error control, thereby elevating converter efficiency. The proposed SMC scheme demonstrates robust performance in countering external disturbances and voltage fluctuations. Incorporating fuzzy adaptive PI control bolsters system adaptability. The controller's capacity to dynamically adjust PI controller gains equips the system to respond adeptly to sudden parameter changes. The strategy was validated through MATLAB simulations, confirming its ability to swiftly stabilize voltage and attenuate oscillations. In conclusion, this paper presents an innovative and effective control approach for DC–DC converters in DC microgrids. The proposed method can be widely used in voltage stabilization control in DC microgrids. Future exploration of applying this strategy to more complex power electronic devices holds promise.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

XZ: Resources, Software, Writing–original draft. YZ: Investigation, Writing–original draft. HJ: Methodology, Validation, Writing–review and editing. MW: Formal Analysis, Validation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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