Research Article

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Harmonic current suppression method of virtual DC motor based on fuzzy sliding mode

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Abstract: In the operation of power grid, the low frequency subharmonics in power lines are easy to cause harmonic current problems. A harmonic current suppression method is constructed based on fuzzy sliding mode and virtual DC motor (VDC). First, the adaptive linear network is introduced to compare and analyze the output value and the actual value in the power line, and the possible harmonic current is obtained, which is detected and discretized. After that, this study adopts Fuzzy sliding mode control (FSMC) strategy for VDC, uses FSMC to participate in on-off control of VDC, and then realizes the suppression of harmonic current in VDC ports. In addition, the model also uses the circuit superposition theorem and the amount of harmonic data to be compensated by FSMC. The whole method uses VDC control technology to ensure the voltage stability of DC bus and load side when the load changes. In this physical experiment, harmonic current generated by load disturbance is eliminated by reducing DC harmonic voltage, so as to achieve the suppression of DC port harmonic current. Experimental results show that the third and fifth harmonics in power lines can be eliminated by this method to a large extent. Therefore, the proposed method can accurately detect and eliminate the harmonic current caused by sudden load change, and then realize the suppression of VDC harmonic current.

Keywords: fuzzy sliding mode control, VDC, harmonic current suppression, ADALINE, voltage stability

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1 Introduction

With the vigorous promotion of distributed power generation such as photovoltaic, wind power, and energy storage, and the increasing proportion of DC load in power terminals, DC microgrid has begun to attract people's attention and achieved great development [1]. However, in the DC microgrid, all distributed power supplies, energy storage devices, and loads are connected to the DC bus through the power electronic converter, which lacks inertia and damping [2]. When the load power in DC microgrid fluctuates, the instantaneous voltage impulse and fluctuation have a great impact on the DC bus voltage, which is not conducive to the stable operation of DC microgrid [3]. virtual DC motor (VDC) is a new technology which can control DC bus voltage smoothly and stably with the development of virtual synchronous machine (VSM). VDC technology can ensure the dynamic stability of the power grid system, and its realization premise is that the voltage and current of the power grid do not exist in harmonics, otherwise it is difficult to achieve the stable output of the load voltage by stabilizing the DC voltage. However, the interface between the VDC and the power line generally has low-order harmonics, which will cause the same frequency harmonics to enter the grid current. Therefore, the stability of power grid is closely related to harmonic content. For the power grid harmonic suppression methods, many scholars have made a discussion. Currently, most foreign scholars use multiple rectifiers, proportional resonance and other methods to suppress harmonic current. Although some research results on harmonic current suppression have been obtained, these methods generally have problems such as poor harmonic current suppression effect and unchanged operation [4,5]. Fuzzy sliding mode control (FSMC) is a control method combining fuzzy control (FC) and sliding mode control (SMC), which is mainly used to control complex objects effectively in uncertain environment. FSMC system has the advantages of high efficiency and robustness for uncertain nonlinear systems. To solve the above problems, this study tries to combine FSMC with VDC technology to ensure the stability of DC voltage and load side voltage during power generation.

The innovations of this research are as follows: (1) Adaptive linear network (ADALINE) is introduced into VDC technology to detect harmonics. (2) Adopt FSMC control strategy, use FSMC to participate in on-off control VDC, and then realize the suppression of harmonic current at VDC ports. The disturbance of nonlinear load is compensated by fuzzy sliding mode method to keep the current and voltage constant. The aim of this study is to promote the rapid development of VDC and provide guarantee for the stable operation of power grid.

2 Related work

VDC technology is mainly applied to improve the stability of DC side voltage. In recent years, many scholars have discussed this issue. Liu *et al.* [6] suggested a commutation deviation correction method on the bias of VDC technology. This method aimed to reach optimal current commutation. In addition, a DC bus electrical reconstructor is proposed to remove the waveform distortion's effect. The test proved the availability of the method for sensorless high-accuracy error correction and optimal current commutation of DC motors. Zhao *et al.* [7] observed that the necessary condition for efficient operation of brushless current motor was to achieve accurate commutation signal. Therefore, this experiment proposed a new method based on virtual zero-line voltage. This method could show higher compensation accuracy and faster compensation speed without current sensor. At last, the method's availability was tested on the 80WBLDC motor. Yang *et al.* [8] carried out research on high-speed brushless DC motor. The experiment aimed to explore the driving method of wireless sensor based on virtual third harmonic back EMF. An envelope of virtual third harmonic back EMF based on oversampling point technique was proposed experimentally. In addition, this study also constructed a new method to suppress negative effects. All the theories proposed in the experiment had been verified on the 60,000 rpm BLDC drive platform. To enhance the inertia of the DC microgrid, Zhi *et al.* [9] proposed a VDC combining the state of charge and the distributed energy storage system. This method balanced power consumption and state of charge by adding the charging and discharging power and state of charge of each energy storage unit to the armature resistance. Finally, the experiment verified that the improved VDC can enhance the DC bus voltage's transient steadiness by testing the DC microgrid. Yan *et al.* [10] found that when the traditional Vienna rectifier was connected to the interface of the electric vehicle charger, it had high requirements for voltage stability. Therefore, it was proposed to apply virtual synchronous motor to Vienna rectifier to improve the adaptability of power grid to large-scale access of electric vehicles. The model built in the experiment could improve the inertia and damping at the interface, and ensured that the vehicle could realize fast charging while improving the stability of the power grid.

FSMC is a control method, which combines FC and SMC. It is mainly applied to effectively control complex objects in uncertain environment. FSMC has the advantages of both FC and SMC, and has good robustness to external interference. In recent years, many researchers in the field of scientific research have begun to study this. Qu *et al.* [11] proposed a FSCM for wireless sensor networks, aiming at the problem that wireless sensor networks are vulnerable to congestion. This method was able to adaptively balance the queue length of the blocking node buffer, thus reducing external interference. A large number of results indicated that the constructed model had higher convergence speed and higher throughput, and could adapt to the change in queue length. To further enhance the network bandwidth utilization of networked control systems, Wang *et al.* [12] established a new FSMC. The sliding surface could ensure the accessibility by synthesizing SMC laws. In addition, to guarantee the asymptotic steadiness of sliding module mechanics, the necessary and sufficient conditions were established by using convex optimization theory and Lyapunov method. The final checking results verified the feasibility of this method. Wu *et al.* [13] proposed a new backstepping FSMC and applied it to the trajectory tracking process of differential wheel mobile robot under external interference. This technology could eliminate the attitude deviation of mobile robot by backstepping control technology. The dynamic SMC could track the speed of the driving wheel. FC could adjust the switch adaptively to alleviate the chattering problem. Results indicated that the proposed model had better precision. Lan *et al.* [14] proposed a FSMC based on fuzzy switch gain adjustment to improve the anti-interference ability of controllable excitation linear synchronous motor. The proposed method introduced an integral term to remove the steady-state error of the system, and used fuzzy logic to eliminate the unknown interference of the system. It was obviously that this method could improve the dynamic performance of the system and had strong practicability. Wang *et al.* [15] designed a model to solve the problem of poor tracking accuracy of welding robot. The controller could effectively identify the external disturbance signal and dynamic uncertainty signal, and then suppressed the chattering phenomenon of the model. The method's good robustness was verified.

To sum up, VDC technology and FSMC have many research results in their respective fields. However, the method of combining the two to ensure the DC stability in the power generation process is still worth exploring at present. Therefore, the FSMC is introduced into the virtual DC generator technology in this research, and the disturbance of nonlinear load is compensated by the FSMC, so as to keep the current and voltage of the power line constant. The experiment aims to provide guarantee for the stable operation of the power grid.

3 Research on harmonic current suppression model of VDC based on fuzzy sliding mode

3.1 VDC control principle

The control method of VDC is relative to the algorithm of VSM. It mainly simulates the motion equation and electromagnetic equation of VSM through reasonable control strategy. Based on the simulation, virtual inertia and virtual damping are introduced. At the same time, frequency modulation and excitation control are introduced to form closed-loop regulation, so that the output of three-phase inverter has better performance [16,17]. The VDC can make the power electronic converter of the DC microgrid have inertia, and can efficiently suppress the voltage fluctuation of the DC bus. The system concept diagram of virtual motor is shown in Figure 1. PV refers to photovoltaic power generation module; L is the equivalent inductance at the grid side; R denotes the equivalent resistance at the grid side; u_a, u_b, and u_c are the output voltage at the inverter side; u_{ga}, u_{gb}, and u_{gc} denote the three-phase voltage of the power grid; i_{Lg}, i_{Lb}, and i_{Lc} represent the output current at the inverter side; and u_{dc} represents the DC voltage output by the PV.

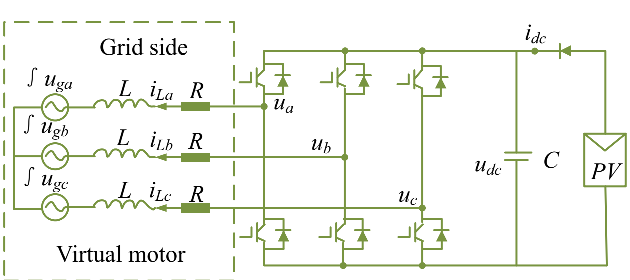

Figure 1: Conceptual structure diagram of virtual motor.

Currently, the research of VDC is mostly about the stability analysis and parameter design of the motor equation. The current and voltage of DC bus and its load are easy to fluctuate under the conditions of power generation and transformation, and its power quality will be reduced. To show the inertia and damping characteristics of the VDC itself [18], and to improve the power quality, the experiment added the mechanical and electromotive force balance equations in the process of restricting its change. The VDC takes the synchronous generator as the reference object, and obtains its specific formula by combining the active-frequency and reactive power-voltage equation as follows [19]:

$$\frac{P_{\mathrm{m}} - P_{\mathrm{e}}}{\omega} = J\frac{\mathrm{d}\omega}{\mathrm{d}t} + D\Delta\omega, \tag{1}$$

$$\Delta\omega = \omega - \omega', \tag{2}$$

$$U = U_0 + D_{\mathrm{q}}(Q_0 - Q), \tag{3}$$

where P_{m} and P_{e} are the mechanical and electromagnetic power of the VDC; ω and ω' are the single angular frequency of the power grid; J is the moment of inertia; D is the damping coefficient; Q_0, Q, and D_{q} are given and measured quantities and voltage sag coefficients under reactive power; U_0 and U are the rated value of voltage and the calculation amount.

3.2 Research on harmonic detection method based on ADALINE neural network

ADALINE is a classical supervised learning algorithm, which is a form of neural network. It uses a gradient descent algorithm to adjust the weights to minimize output errors and find the best classification bounds. Adaline has a linear activation function that can be used to process linearly separable data. It can be viewed as an improved version of the perceptron algorithm because it uses continuous activation functions instead of simple step functions. By comparing the network output and the target output, the ADALINE method constantly adjusts the network weight to minimize the error between the network output and the target output. ADALINE algorithm has the characteristics of nonlinearity and nonlocality, and has strong ability to calculate large amounts of data. Therefore, it is suitable for signal detection, extraction, and noise reduction. In view of this, this study applies ADALINE neural network to detect harmonics. The harmonic detection process based on ADALINE network is shown in Figure 2. In Figure 2, the harmonic sine and cosine signals are generated by the coordinate rotation digital computer. The amplitude of direct flow and harmonic volume is

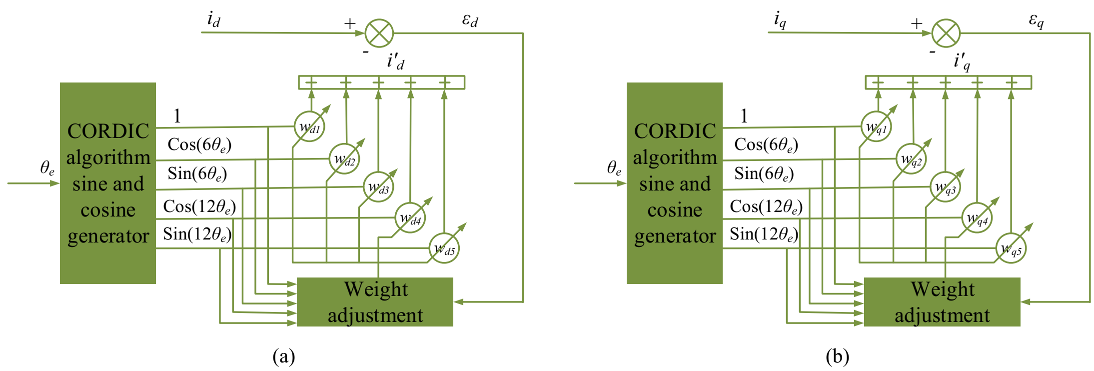

Figure 2: Harmonic detection method based on ADALINE. (a) *D*-axis current harmonic extraction and (b) *Q*-axis current harmonic extraction.

regarded as the weight of ADALINE network, and LMS algorithm is used to update and adjust.

First, the current signal with harmonic (n times) on both sides of the VDC is discretized to obtain Eq. (4) [20].

$$y(n) = \sum_{m=0}^{M} \left[a_m \sin\left(\frac{m}{N}\dot{\omega}n\right) + b_m \cos\left(\frac{m}{N}\dot{\omega}n\right)\right], \quad (4)$$

where the maximum number of spectral lines of the VDC is expressed by M, the number of cycles contained in the analysis window is described by N, the weight coefficients of the sine and cosine terms of the m-th harmonic are expressed by a_m and b_m, respectively, the number of certain frequency spectral lines is expressed by m, and $\frac{m}{N}$ and $\dot{\omega}$ are the order and angular frequency of harmonics, respectively.

$$y(n) = \sum_{m=0}^{M} c_m \sin\left(\frac{m}{N}\dot{\omega}n + \varphi_m\right), \quad (5)$$

$$c_m = \sqrt{{a_m}^2 + {b_m}^2}, \quad (6)$$

$$\varphi_m = \begin{cases} \arctan\dfrac{a_m}{b_m} \\ \pi + \arctan\dfrac{a_m}{b_m}, \end{cases} \quad (7)$$

where c is the amplitude of harmonic signal, andφ is its phase angle. Determine the harmonic frequency $\dot{\omega} = 2\pi f$ and multiply by the number of harmonics. Select the input sine and cosine vectors through ADALINE neural network, and after cycling k times, the calculation formula of input vector x_k can be obtained at the point n of the current signal with possible harmonics, as shown in Eq. (8).

$$x_k = \begin{bmatrix} \sin\left(\frac{0}{N}\dot{\omega}n\right) \cos\left(\frac{0}{N}\dot{\omega}n\right) \sin\left(\frac{1}{N}\dot{\omega}n\right) \\ \cos\left(\frac{1}{N}\dot{\omega}n\right) \cdots \sin\left(\frac{m}{N}\dot{\omega}n\right) \cos\left(\frac{m}{N}\dot{\omega}n\right) \end{bmatrix}^T. \quad (8)$$

When the harmonic frequency $\dot{\omega}$ is a fixed value, the position of the current signal n point that may have harmonics is variable. The output weight vector is calculated by Eq. (9).

$$w_k = [a_0 b_0 a_1 b_1 \cdots a_m b_m]. \quad (9)$$

ADALINE network output is as shown in Eq. (10).

$$y_k(n) = w_k x_k. \quad (10)$$

There is an error signal between the current signal that may have harmonics input by ADALINE network and the actual harmonic current signal, whose formula is expressed as follows:

$$e_k(n) = y(n) - y_k(n), \quad (11)$$

where $y_k(n)$ represents the actual output harmonic current signal, and $y(n)$ indicates a current signal that may have harmonics. Take the error signal $e_k(n)$ as the input, and modify the step size according to the minimum mean square root of the variable step size to obtain the corresponding error accuracy $w_k = (a_m, b_m)$. Meanwhile, output a fine-tuning signal for the weight vector and calculate the step size of the weight vector based on signal overlap.

$$\Delta w_k = \mu_k e_k(n) x_k, \quad (12)$$

where μ represents the modified step size. Introduce learning rate γ_s into step size, $\gamma_s > 0$. The new step length is $\mu_{k+1} = \alpha\mu_k + \gamma_s \|\bar{P}\|^2 e^2(k)$, wherein $0 < \alpha < 1$. The calculation formula of smooth gradient vector $\bar{P}$ obtained from the above content is shown in Eq. (13).

$$\bar{P}(k) = \beta\bar{P}(k-1) + (1-\beta)e_k(n)x_k, \quad (13)$$

where $0 < \beta < 1$. β is a smoothing factor of approximately 1. Combined with formulas (5)–(7), the spectrum of the voltage and current signal to be measured for the VDC can be obtained.

3.3 Construction of harmonic current suppression model based on FSMC and VDC

FSMC is a kind of control method that combines FC and SMC. It is mainly used in uncertain environment for effective intelligent control of complex objects. This control method has strong independence and robustness against various disturbances. It has the advantages of the two control modes. The characteristic of FSMC is that it is adjusted by fuzzy logic in the approaching stage to control the function of the whole system. The core idea of SMC is to control the state quantity to move near the sliding mode. Therefore, the main content of the SMC is the ability to maintain the motion of the state variables near the sliding mode surface [5,20]. In recent years, the relevant theories of fuzzy logic control system have become increasingly mature. This experiment combines SMC with FC, designs sliding mode surface and uses fuzzy reasoning mechanism, and finally deblurring [21]. The significance of the above operation is to reduce the adverse effects of switching gain and symbol function in the original design controller, so as to achieve the purpose of optimization and improvement.

The experiment combines the harmonic detection of VDC and the theorem of circuit superposition to extract the h harmonic of the control when the VDC works stably [22]. After that, the experiment calculates the amount of data for harmonic compensation through the FSMC. Meanwhile, the harmonic current generated by load disturbance is eliminated by reducing the harmonic voltage. In the design process, the harmonic voltage of the VDC interface is set to 0, and the calculation formula of the terminal voltage is obtained through the load part of the harmonic equivalent circuit, as shown in Eq. (14) [23].

$$\overline{V_0} = E\langle\delta - Z_0 I\langle\theta = E\cos\delta - Z_0 I\cos\theta + j(E\sin\delta - Z_0 I\sin\theta), \tag{14}$$

where E and I denote the voltage and current of DC bus, respectively, $\theta = 90°$, Z_0 and δ, respectively, represent the phase difference between the equivalent impedance and the voltage and current sources, $\sin\delta \approx \delta$, and $\cos\delta \approx 1$.

The output of FSMC can realize the size control of variable u through FSMC rules. Finally, the stability condition $s\dot{s} < 0$ can be satisfied. Assuming that the detected currents with harmonics i^*_{Ca}, i^*_{Cb}, and i^*_{Cc} are current signals, the actual compensation currents are i_{Ca}, i_{Cb}, and i_{Cc}, respectively, *i.e.*, the detected currents are tracked and controlled by SMC. Set the tracking error and change rate as e_i and ec_i, respectively, to obtain Eq. (15) [15].

$$\begin{cases} e_i = i^*_{ci} - i_{ci} \\ ec_i = \dfrac{\mathrm{d}(i^*_{ci} - i_{ci})}{\mathrm{d}t} \end{cases} \tag{15}$$

where $i = a, b, c$. The sliding surface of SMC is defined in Eq. (16).

$$S_i = c_i e_i + d_i ec_i, \tag{16}$$

where $c_i > 0$, $d_i > 0$, and $i = a, b, c$. Input $(s, \dot{s})$ into the fuzzy controller, fuzzify it, and then obtain the fuzzy variable of the FSMC according to the FC rules. The final output is the fuzzy output variable after the de-blurring process is completed. Then, the explicit output of FSMC is obtained. Meanwhile, the fuzzy dataset is defined as: PB = positive large, PM = positive middle, PS = positive small, ZO = zero, NS = negative small, NM = negative middle, NB = negative large. Applying the fuzzy rule "If S is A and S is B, then u is C," the structure of the FSMC is shown in Figure 3.

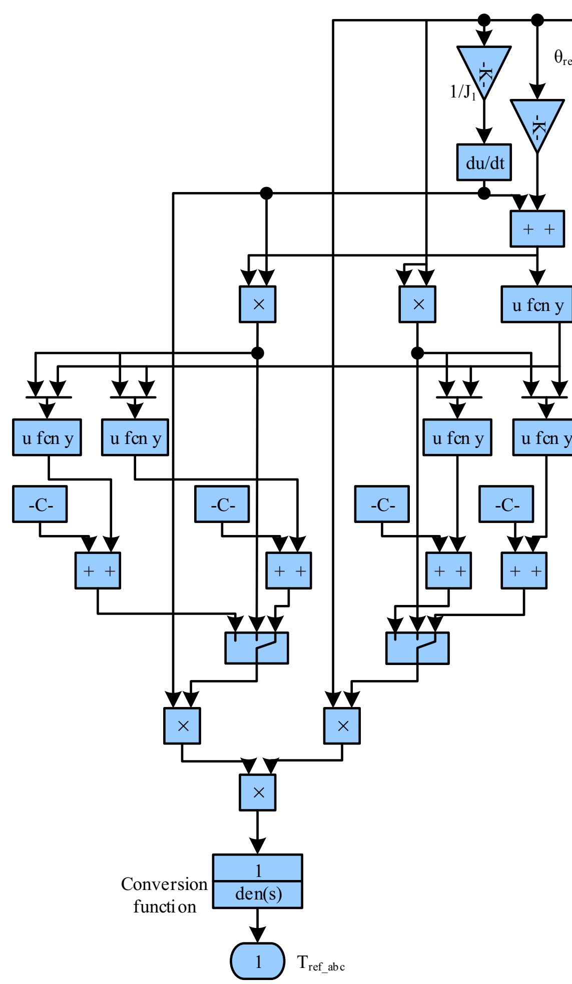

Figure 3: Fuzzy sliding mode controller.

Therefore, the current amplitude and angular frequency of the harmonics to be cleared can be obtained by calculation. In addition, the given value of harmonic voltage and current can also be obtained through the combined transformation of voltage and coordinate. To sum up, the experiment uses FSMC to participate in the on-off control of VDC, and then realizes the suppression of harmonic current at the VDC port.

4 Performance verification of VDC harmonic current suppression model based on fuzzy sliding mode

To verify the performance of the harmonic current suppression model combining the FSMC and the VDC, the experiment is conducted in the power grid simulation laboratory of the Electric Power Research Institute of a provincial power company limited by the State Grid in the semi-physical simulation platform RTLAB. In the experiment, the data are collected and analyzed by the Audley data acquisition system DEWE5000 and the daily 3198 power quality analyzer. The experimental parameters are set as follows: the nonlinear load active power P_{ref} is 200 W. The load reactive power Q_{ref} is 0 kVar. Select the voltage source module in the RTLAB module, and its rated voltage is 220 V. The load resistance is 50 Ω, inductance is 20 mH, the capacitance is 1,500 μF, the sampling frequency is set to 6.4 kHz during measurement, and the voltage regulator is used for voltage control.

Figure 4 shows the convergence test results of ADALINE. As shown in Figure 4, when iteration is performed for 57 times, both Error and Loss values of ADALINE dropped to the lowest point, and the convergence of the model tended to be stable with the increase in iterations, indicating that ADALINE had good convergence performance.

To verify the effect of VDC on the circuit converter, the VDC is introduced into the control system of the circuit converter. Figure 5 shows the relationship between the amplitude and phase of the vibration before and after adding the VDC and the speed, namely, the Bode diagram. The curve in the figure shows that after adding the VDC, the range of its turning rate is greatly reduced. At this time, the network bandwidth will also decrease. In addition, the phase margin will also be greatly increased. The above situation shows that the first-order inertia of the VDC control link plays an important role in improving the performance of the overall converter.

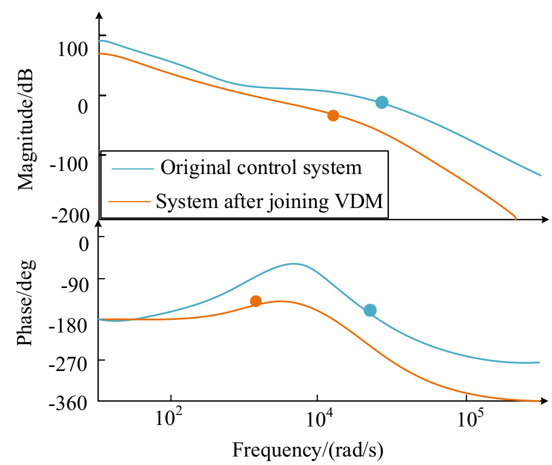

Figure 5: Bode diagram before and after adding VDC.

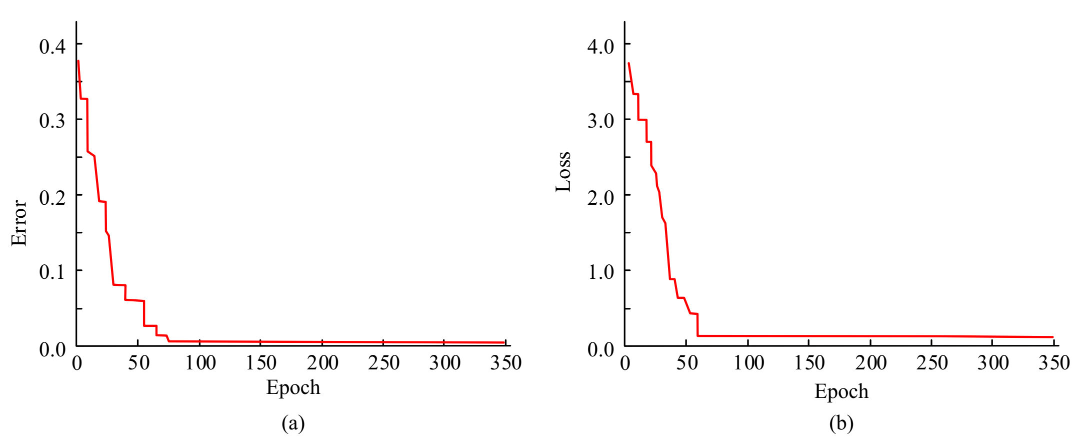

Figure 4: Convergence performance of ADALINE. (a) Error and (b) loss.

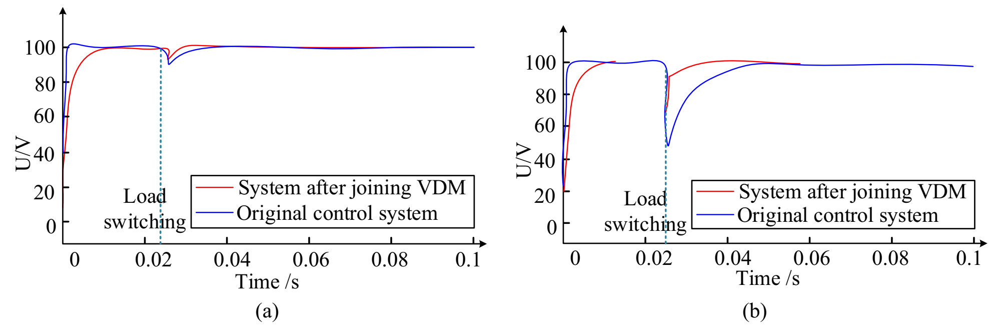

Figure 6: System corresponding diagram before and after adding VDC technology. (a) Switch 1 Ω resistance at load side and (b) Switch 10 Ω resistance at load side.

To explore the influence of the control system of the VDC link on the steadiness of the overall converter control system, the experiment chooses to load the load side of the circuit once at a certain time after the output voltage is stable. The load resistance values are set to 1 and 10 Ω, respectively. The system response results of the simulation experiment are shown in Figure 6. In both cases, the addition of VDC increases the rise time of the original stable system, so the system's response speed slows down. In addition, due to the disturbance of small load, the voltage fluctuation of the original control system is large. However, the system is relatively more stable after the introduction of VDC control technology, which verifies the effectiveness of virtual DC click to suppress the voltage fluctuations.

Subsequently, the experiment verifies the current tracking control error of the VDC method based on FSMC proposed in this study, and the results are shown in Figure 6. From Figure 7, it can be seen that the tracking error of the current in the power line without the method proposed in this study is relatively large, and the error is significantly reduced after the method proposed in this study is applied. Thus, it is verified that the method can efficiently prevent the buffeting of power lines in the case of load disturbance, thus improving the accuracy of current tracking control.

In the same power line, the suppression effect of harmonics in the current before and after the application of this method is analyzed. From Figure 8, it can be seen that when this method is not used, there are third and fifth harmonics in the power line. After applying this method, it can be clearly seen in Figure 8(b) that the third and fifth harmonics are almost completely eliminated. The harmonic condition is obviously improved, which verifies that the method proposed in this study has excellent harmonic current control effect. The proposed method can better control the power quality of power lines, effectively maintain the energy output of power equipment, and ensure the stable operation of power lines.

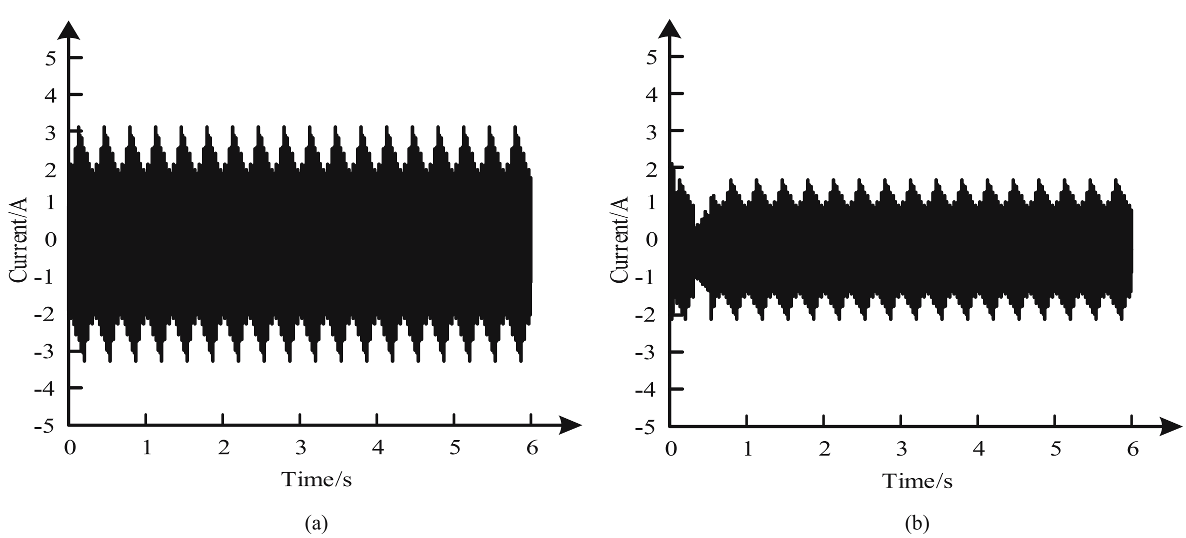

Figure 7: Current tracking error before and after using this method. (a) Tracking error before use and (b) tracking error after use.

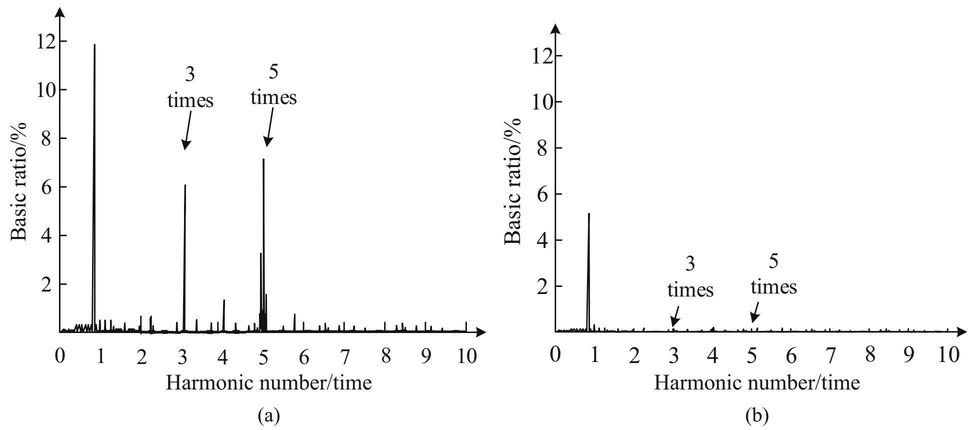

Figure 8: The harmonics before and after using this method. (a) Harmonic condition before use and (b) Harmonic condition after use.

The results of the FSM harmonic current suppression method proposed in this study are shown in Figure 9 when there are third and fifth harmonics in the power line. From Figure 9, before the application of the method, the current waveform has vibration and shows irregular shape. After adopting the FSMC proposed in this study, the current waveform is relatively smooth and close to the standard sine wave. This shows that the third and fifth harmonics of the current in the power line have been successfully suppressed and attenuated. The harmonic suppression method of VDC based on FSMC constructed in this experiment has a small control delay, and can effectively achieve the suppression of harmonic current of power lines without static error.

Connect the nonlinear load in the experimental power line, and the experimental current waveform before and after the application of this method is shown in Figure 10. The current waveform connected to nonlinear load has serious distortion before applying the proposed method. After applying this method, the current waveform is obviously enhanced and the harmonics are reduced. The results show that the quality of current waveform has been significantly improved, and the method can efficiently suppress the disturbance of nonlinear load.

To further verify the dynamic response capability, the compensation effect under load change is taken as an indicator in the experiment. According to the results shown in Figure 11, in the case of load changes, the curve of compensation current is significantly more rounded after the application of this method. The overall curve has no deformation and is more stable. However, when this method is not applied, the current is seriously deformed. From the comparison of the two methods, it can be seen that this

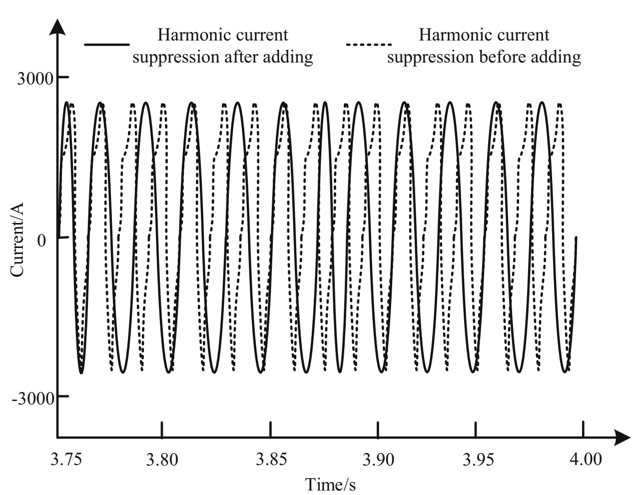

Figure 9: Harmonic current suppression before and after using this method.

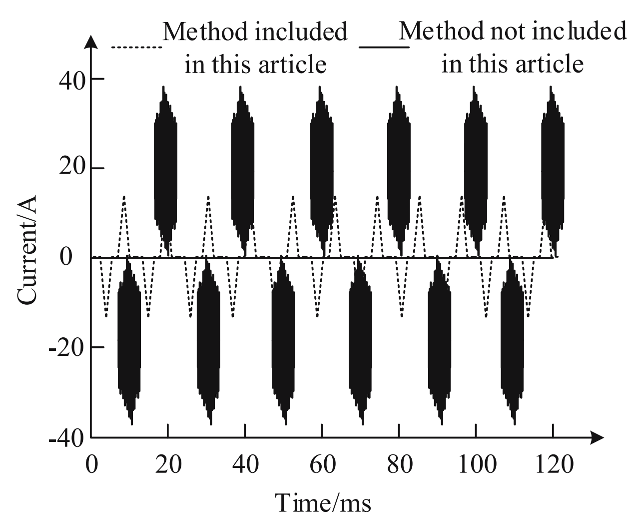

Figure 10: Nonlinear load suppression before and after using the proposed method.

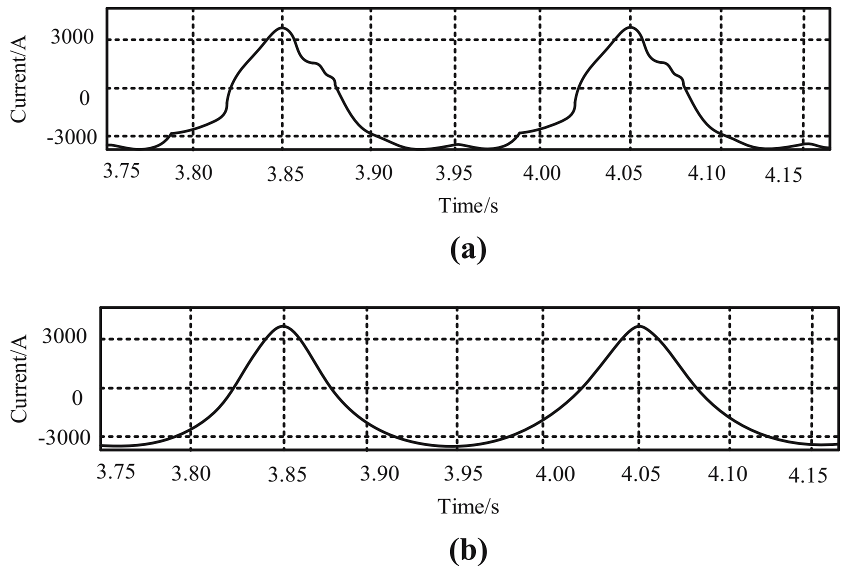

Figure 11: Compensation effect under load variation. (a) Load current and (b) compensation current.

method can effectively compensate for the current when the load changes, achieving the experimental purpose.

5 Conclusion

Aiming at the low frequency harmonics of power lines in the process of power grid operation, this study proposes a harmonic current suppression method based on FSMC and VDC. This method uses VDC control technology to ensure the voltage stability of DC bus and load side in case of sudden load change, and incorporates fuzzy sliding mode technology into the original suppression method to calculate the amount of harmonic data to be compensated. Among them, ADALINE network is also used for discrete processing of current signals that may have harmonics in power lines. The results indicate that the voltage fluctuation of the control system is smaller and more stable when the load resistance is 1 and 10 Ω, respectively. The verification results of current tracking control error show that the suggested model can efficiently prevent buffeting of power lines in the case of load disturbance. In terms of harmonic elimination, the proposed method almost eliminates the third and fifth harmonics. It not only improves the quality of DC voltage, but also improves the power quality of power lines. And when the current waveform of nonlinear load is connected, the model improves the current waveform and reduces the harmonics, and improves the quality of the current waveform. Therefore, the proposed method can accurately detect and eliminate the harmonic current caused by sudden load change, effectively reduce the buffeting of power lines, and thus achieve the suppression of harmonic current of VDC without static error. The limitation of this study is that it fails to verify the complexity of FC, which can be used as the next research direction.

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