An Improved High-Frequency Common-Mode Voltage Injection Method in Modular Multilevel Converter in Motor Drive Application

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Abstract—**This paper discusses the application of Modular Multilevel Converter (MMC) in motor drive. In the startup and low-speed operation, large capacitor voltage ripples appear in MMC. This paper proposes an improved high-frequency common-mode voltage injection method. In the improved method, the amplitude of injected voltage is varying according to the instantaneous value of the output voltage, and it can take full use of the arm voltage margin. This will lead to further reduction in the circulating current and higher efficiency. Both three-phase and single-phase cases are discussed, and comparisons are made between the existing control method and the improved one. This method can be more effective in the single-phase system since there is no interaction of three-phase output voltages. MMC simulation model built in PSCAD/EMTDC verifies the validity.**

Keywords—modular multilevel converter (MMC); motor drive; voltage ripples; improved high-frequency injection; circulating current reduction

I. INTRODUCTION

Recently, the Modular Multilevel Converter (MMC) has gained much attention from the researchers, and it is a competitive topology for medium- and high- power applications such as High Voltage Direct Current (HVDC), power quality control, motor drive [1-5]. However, in motor drive, the MMC suffers large voltage ripples in Submodule (SM) capacitors. And this problem becomes more severe when operating in startup and low-speed region [5].

To handle the voltage ripples problem and ensure safe operation of MMC, several control strategies have been proposed [5-10]. In [6-7], the injection of a proper selected second order circulating current or combination of second and fourth order circulating currents is discussed. The proposed method can be effective only with high modulation index. Since in Motor drive application, the MMC system operates in a large range, the application of this method is limited. The high-frequency common-mode voltage and circulating current injection control method has been presented in [5, 8-10]. Firstly, the sinusoidal common-mode voltage and circulating current is discussed [5]. The proposed method can effectively suppress the voltage ripples. However, the large injected circulating current leads to high system loss. To reduce the circulating current requirement, in [8], the authors improved the method by using sinusoidal+3rd harmonic wave and square wave to reshape the injected voltage and current. The peak value of the circulating current can be reduced by 50% in square wave injection. A combination of square wave voltage and sinusoidal wave circulating current injection is discussed [9], which avoids the control difficulty of square wave circulating current injection. A ripple limit is set to avoid full compensation of voltage ripples in [10]. In this method, certain amount of ripple power is buffered by the SM capacitors, and the circulating current needed will decrease. In addition, an Active Cross-Connected MMC (AC-MMC) and a Flying-Capacitor MMC (FC-MMC) are also proposed [11-12]. The new MMC topologies mitigate the common-mode voltage for AC motors.

However, in these methods, the amplitude of injected high-frequency common-mode voltage is determined based on the amplitude of the output voltages. In the operation, output voltages in the arms varies in a sinusoidal way, this will cause waste of the arm voltage margin. In this paper, the amplitude of the injected high-frequency voltage is redefined based on the instantaneous output voltages instead of its amplitude in the conventional method. In this way, the circulating current can be further decreased. Both three-phase and single-phase cases are discussed. The improved method can suppress the ripples with smaller circulating current, and it is more effective in single-phase case.

The outline of this paper is organized as follows: section II describes the circuit configuration and analyzes the voltage ripples in the SM capacitors; section III develops the improved control method in three-phase and single-phase cases, respectively; section IV shows the simulation results in PSCAD/EMTDC software environment, which verifies the validity of the proposed method; section V gives the conclusions.

II. SYSTEM DESCRIPTION

A. Circuit Configureation

Fig. 1 shows the circuit configuration of one typical three-phase MMC system. In each phase, there are two identical arms,

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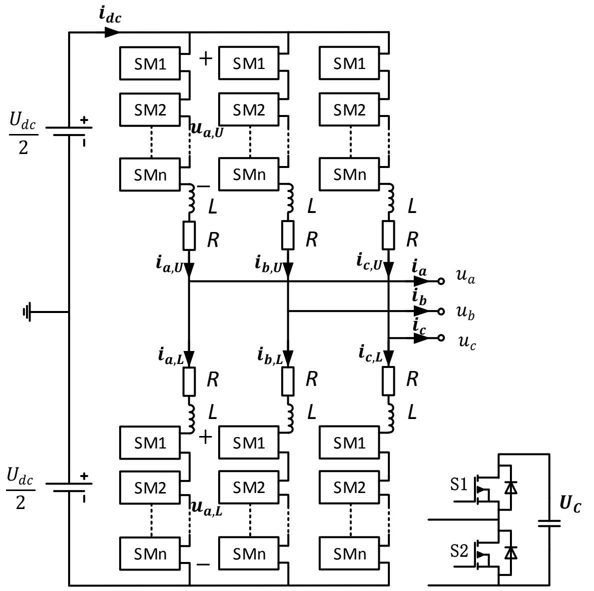


Fig. 1. MMC circuit configuration.

namely upper- and lower- arms. Each arm is composed of *N* half-bridge SM, one arm inductor and one equivalent resistor which indicates the loss.

B. Voltage Ripples Analysis

In this paper, the sinusoidal wave injection method is used to illustrate the voltage ripples elimination control. For other injection method, the analysis process is similar. Based on the MMC working principles and high-frequency components injection control method, the mathematical expressions of the arm voltages and currents can be written as:

$$\begin{cases} u_{x,U} = \frac{U_{dc}}{2} - u_x - u_{h,x} \\ u_{x,L} = \frac{U_{dc}}{2} + u_x + u_{h,x} \\ i_{x,U} = I_{dc,x} + i_{h,x} + \frac{i_x}{2} \\ i_{x,L} = I_{dc,x} + i_{h,x} - \frac{i_x}{2} \end{cases} \tag{1}$$

The subscript *x=a, b, c* denotes the three phases; u_x and i_x represent the output voltages and currents; $u_{h,x}$ and $i_{h,x}$ indicate the injected high-frequency voltages and currents; $I_{dc,x}$ is the DC circulating currents. The definition of output and high-frequency components are expressed in equation (2), where U_o, I_o, U_h and $I_{h,x}$ are amplitudes of the AC components, the α_x and φ_x are the phase angles of MMC output voltages and currents, the ω and ω_h denote the output angular frequency and the angular frequency of injected high-frequency components, respectively.

$$\begin{cases} u_x = U_o \sin(\omega t + \alpha_x) \\ i_x = I_o \sin(\omega t + \varphi_x) \\ u_{h,x} = U_h \sin(\omega_h t) \\ i_{h,x} = I_{h,x} \sin(\omega_h t) \end{cases} \tag{2}$$

According to the arm voltages and currents, the instantaneous power of upper- and lower- arms can be calculated by:

$$\begin{cases} p_{x,U} = u_{x,U} i_{x,U} = \frac{U_{dc} I_{dc,x}}{2} - \frac{u_x i_x}{2} + \frac{U_{dc} i_x}{4} - u_x I_{dc,x} \\ \quad -u_{h,x} i_{h,x} + \frac{U_{dc} i_{h,x}}{2} - u_x i_{h,x} - \frac{u_{h,x} i_x}{2} - u_{h,x} I_{dc,x} \\ p_{x,L} = u_{x,L} i_{x,L} = \frac{U_{dc} I_{dc,x}}{2} - \frac{u_x i_x}{2} - \frac{U_{dc} i_x}{4} + u_x I_{dc,x} \\ \quad +u_{h,x} i_{h,x} + \frac{U_{dc} i_{h,x}}{2} + u_x i_{h,x} - \frac{u_{h,x} i_x}{2} + u_{h,x} I_{dc,x} \end{cases} \tag{3}$$

The first two terms in equation (3) indicate the power balance between AC and DC side. The sum of these two terms should be zero to ensure stability. This will be achieved by adjusting the DC circulating current. The third and fourth terms cause the fundamental power oscillation and are the main reasons for the capacitor voltage ripples in low-speed operation. The fifth term is the power introduced by the high-frequency components injection control method, and it consists of a DC power component $\frac{U_h I_{h,x}}{2}$, which will compensate the fundamental power oscillation, and a high-frequency power component. These high-frequency power components in (3) have small impact on the SM capacitor voltage and are negligible in the analysis.

Through the discussion above, the power equation for SM capacitor voltage ripples elimination can be obtain:

$$-\frac{U_{dc} i_x}{4} + u_x I_{dc,x} + \frac{U_h I_{h,x}}{2} = 0 \tag{4}$$

And consequently, solving equation (4) leads to the amplitude of corresponding high-frequency circulating current:

$$I_{h,x} = 2\left(\frac{U_{dc} i_x}{4} - u_x I_{dc,x}\right) / U_h \tag{5}$$

III. IMPROVED CONTROL METHOD

The details of MMC control structure have been well investigated and can be found in [8-12]. The following

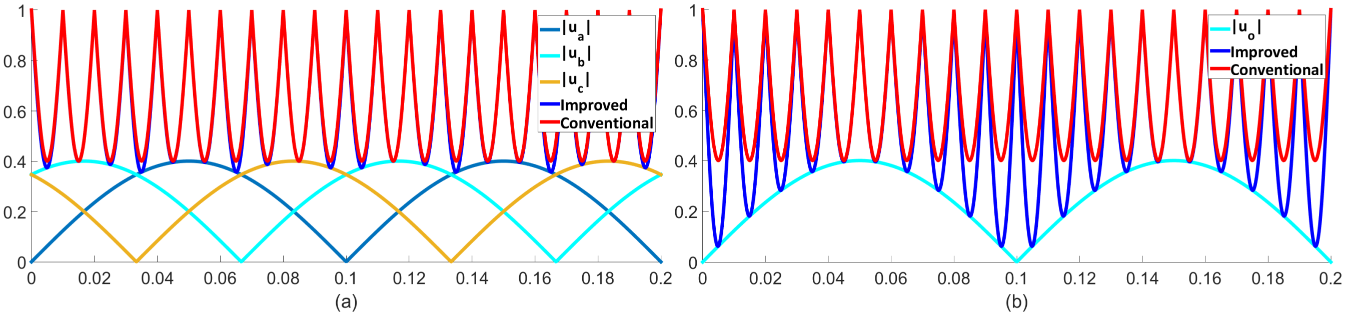
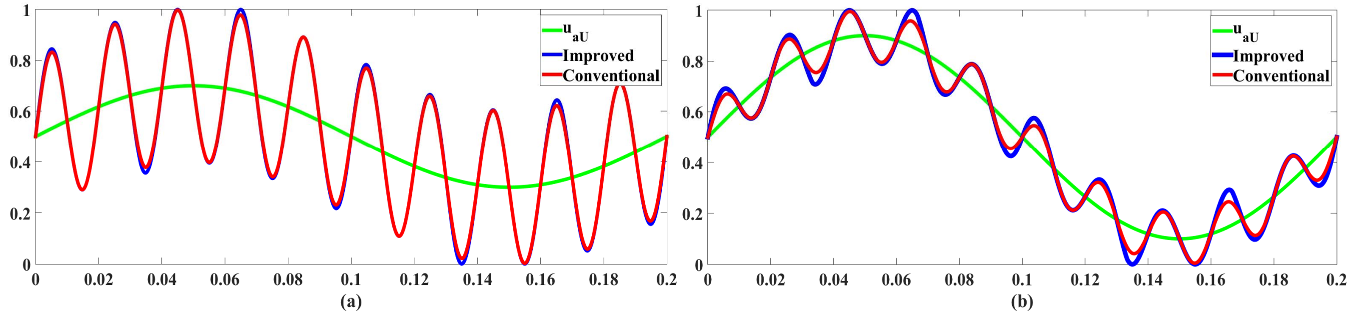
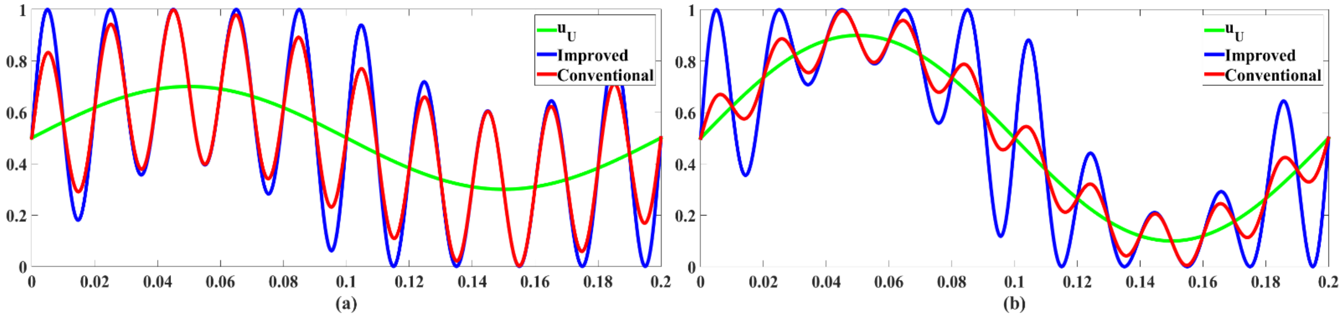


Fig. 2. MMC output voltages and injected high-frequency voltages, (a) three-phase case, (b) single-phase case.



(a) (b)

Fig. 3. Phase a upper-arm voltage, three-phase case.



(a) (b)

Fig. 4. Upper-arm voltage, single-phase case.

subsections mainly focus on the improved high-frequency common-mode voltage injection method.

A. Three-phase Case

In the conventional method, the amplitude of high-frequency common-mode voltage U_h is defined in a complementary way with output voltage amplitude U_o, shown in equation (6), to avoid over modulation.

$$U_h = \frac{U_{dc}}{2} - U_o \tag{6}$$

Fig. 2(a) shows one case where the modulation index is $m = 0.6$. This leaves $m_h = 0.4$ for the high-frequency voltage injection. From this figure, one can find that the output voltages vary in a sinusoidal way and they will not always be at their maximum value, i.e., its amplitude U_o, and sometimes the u_x could be small. Therefore, there is the possibility to augment the amplitude of the injected high-frequency voltage. The author here consider to redefine the amplitude of the high-frequency voltage. Instead of being limited by the amplitude of output voltages, the amplitude of high-frequency voltage is calculated according to the instantaneous output voltages:

$$U_{h,improved} = \frac{U_{dc}}{2} - \max(|u_a|,|u_b|,|u_c|) \tag{7}$$

In the improved method, the amplitude of high-frequency voltage varies with the output voltages. And it is able to ensure a full use of voltage margin at any time. Blue line in Fig. 2(a) verifies the validity.

Take phase a upper-arm for example. Its voltage can be represented as

$$u_{a,U} = \frac{U_{dc}}{2} - u_a - U_{h,improved}\sin(\omega_h t) \tag{8}$$

Base on (8), Fig. 3 shows the numerical calculation in MATLAB of the upper-arm voltage (normalized) under conventional and improved method, for $m = 0.4, m = 0.8$, respectively. The green lines denotes the original arm voltage without high-frequency voltage injection; the red lines shows the arm voltage with conventional injection method; the blue lines represent the arm voltage under improved injection method. The results show that amplitude of injected voltage in the MMC system increases by using the new calculation method. In addition, the improved method is more advantageous in high modulation operation, observed in Fig. 3(b). Then, the amplitude of high-frequency circulating current can be modified as:

$$I_{h,x,improved} = 2\left(\frac{U_{dc}i_x}{4} - u_x I_{dc,x}\right)/U_{h,improved} \tag{9}$$

The improved method will result in a smaller high-frequency circulating current in the system, and increase the efficiency.

B. Single-phase Case

In three-phase case, the amplitude of high-frequency voltage is impacted by the three-phase output voltages, because over modulation should be avoided in any phase. This limits the usable voltage margin. As seen in Fig. 2(a), only small part can be used to augment the amplitude.

While in single-phase system, only one phase output voltage needs to be considered. In Fig. 2(b), there is large margin in the arm voltage, and the amplitude of high-frequency voltage can be greatly increased. Hence, in the improved method, the amplitude is redefined as:

$$U_{h,improved} = \frac{U_{dc}}{2} - |u_o| \tag{10}$$

Blue line in Fig. 2(b) shows the new high-frequency voltage. With equation (10), the voltage margin is fully utilized. And similarly, Fig. 4 depicts numerical calculation in MATLAB of the upper-arm voltage (normalized) of the conventional and improved method in single-phase case. Apparently, without the influence of other phases, the improved method is more attractive. Fig. 4(a) shows the $m = 0.4$ case. And at certain time, the voltage amplitude is almost doubled compared with the conventional one. And in $m = 0.8$ case, four times larger amplitude can be reached at some time intervals. So the improved method is favorable for the current reduction.

IV. SIMULATION VERIFICATION

Both three-phase and single-phase MMC simulation model are built in PSCAD/EMTDC software environment. The system parameters are listed in table I.

In the existing lectures, the control performance of the high-frequency common-voltage injection method has already been tested. The simulation in the paper focuses on the high-frequency circulating current reduction. Thus, a resistance and inductance (RL) load is selected here to connect MMC system to confirm the validity of the improved method.

TABLE I. THE MMC PARAMETERS

Parameters	Values
DC-link Voltage	8kV
SM Capacitor Voltage	2kV
Number of SM per Arm	4
SM Capacitance	3mF
Arm Inductance	2mH

A. *Three-phase case*

Fig. 5 shows the simulation results for verifying the steady-state performance of the improved high-frequency common-mode voltage injection method in three-phase system. The MMC system feeds a Δ-type RL load. The output frequency is set to be $f_o = 10Hz$. And the frequency of injected high-frequency components is chosen as $f_h = 200Hz$.

The waveform of the injected high-frequency voltage is presented in Fig. 5(a). The red line shows the result of conventional voltage amplitude calculation method. Its amplitude remains the same all the time. While by adopting the improved method, the amplitude is increased at some time intervals which corresponds to the analysis in Section III. And the high-frequency circulating currents are shown in Fig. 5(b), with the help of improved method, the current has been reduced. Fig. 5(c) shows the zoomed view of circulating current. There is an about 5% reduction in some period of the operation. As discussed in Section III, the effectiveness of the improved method in three-phase system is limited due to the interaction of three-phase output voltages. But it is still an applicable method for current reduction.

Fig. 5(d) shows the individual SM capacitor voltages under the improved method. The voltages are regulated at their rated value 2kV with little voltage ripples, confirming that the improved method will not influence the existing MMC control structure.

B. *Single-phase case*

The results of single-phase system is depicted in Fig. 6. Firstly, the injected high-frequency voltage is shown in Fig. 6(a). Without the interaction of three-phase output voltages, the amplitude of the high-frequency voltage has been largely augmented using equation (10).

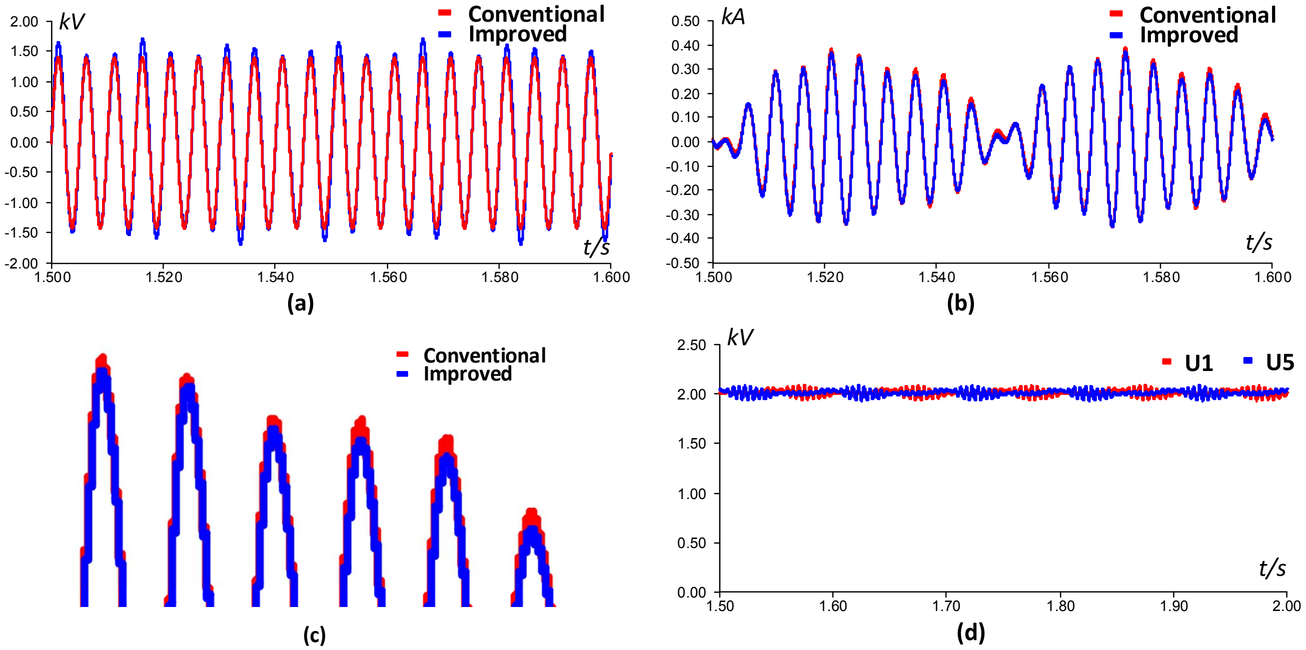


Fig. 5. Simulation results, three-phase case.

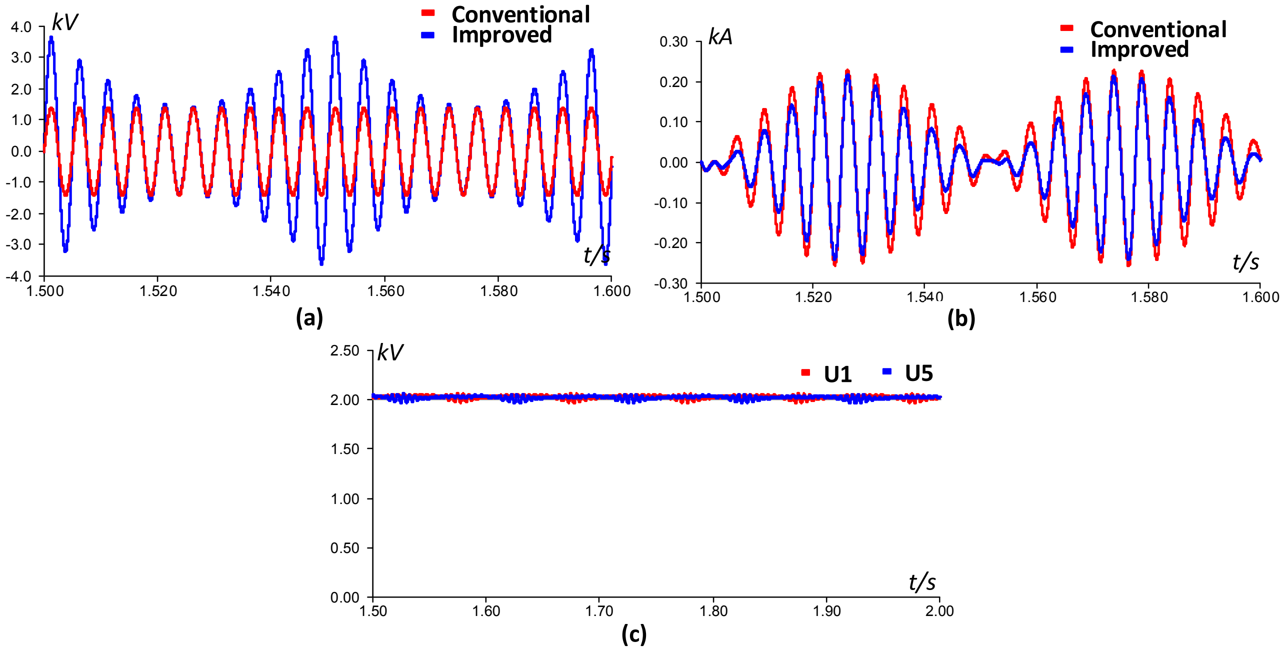


Fig. 6. Simulation results, single-phase case.

In the simulated system, the maximum amplitude of injected high-frequency voltage in the improved method can be much larger than that in the conventional one, which leads to an obvious reduction in the corresponding circulating current. Almost 20-40% decrease is observed in Fig. 6(b). And it will finally be reflected in the system efficiency. Meanwhile, the SM capacitor voltages are also presented in Fig.6 (c) which are well regulated.

V. CONCLUSION

In this paper, the voltage ripples problem for MMC based motor drive is discussed. An improved high-frequency common-mode voltage injection method is proposed. In this method, the system can fully use the arm voltage margin to achieve a larger voltage injection. Therefore the injected high-frequency circulating current in the system can be reduced. Both three-phase and single-phase cases are analyzed. And the improved method can be more effective in the single-phase system since there is no interaction of three-phase output voltages. Simulation in PSCAD/EMTDC verifies the validity.

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