

# A generic PWM strategy for multi-leg VSI-fed machine drives

Wang Wei Zhang Jinghao Cheng Ming

(School of Electrical Engineering, Southeast University, Nanjing 210096, China)

**Abstract:** A generic pulse width modulation (PWM) strategy is proposed for the multi-leg voltage source inverter (VSI). First, the multi-leg VSI is modeled, which is independent from the load structure. Secondly, the proposed PWM strategy is deduced by inverting the mathematical model of the multi-leg VSI. According to the relationship between the leg number of VSIs and the phase number of electrical machines, the multi-leg VSI-fed machine drives are classified into two types: matched and unmatched applications. The leg numbers of VSIs and the phase number of electrical machines are equal in matched applications while they are different in unmatched applications. The existing PWM strategies cannot be directly used for both matched and unmatched applications. However, the proposed PWM strategy can be general for both matched and unmatched applications, and no modifications are required. The effectiveness of the proposed PWM strategy is verified by experimental results.

**Key words:** pulse width modulation (PWM); multi-leg voltage-source-inverter (VSI); carrier-based PWM; machine drives

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Nowadays, pulse-width-modulation (PWM) voltage source inverters (VSIs) have been widely utilized in machine drives. One typical application is the three-phase machine drive, in which the three-phase electrical machine is fed by one three-leg VSI<sup>[1–6]</sup>. For the three-phase machine drive, space vector PWM (SVPWM) and carrier-based PWM (CBPWM) are the two most popular PWM strategies<sup>[7]</sup>. In SVPWM, a reference space vector is synthesized by two selected active space vectors and then the duration time of each selected active space vector is calculated. In CBPWM, modulation signals are compared with triangular carrier signals to generate switch states, while the classical modulation signals are the ratios between reference phase voltages and the half dc-link

voltage. Meanwhile, the multi-leg VSI is also widely applied due to the development of multiphase electrical machines and the  $n$ -phase electrical machine is usually supplied by one  $n$ -leg VSI<sup>[8–13]</sup>. Correspondingly, the PWM strategies should be extended from three-leg VSIs to multi-leg VSIs. For the  $n$ -phase electrical machine, there will be  $2^n$  space vectors. Moreover, the number of space vectors increases with the phase number of electrical machines, which makes the implementation of multiphase SVPWM complex and difficult<sup>[14]</sup>. However, CBPWM has no such problems and it can be easily extended to control the multi-leg VSIs. Obviously, CBPWM is simpler than SVPWM in multi-leg VSI applications. An important feature that should be highlighted is that the leg number of VSIs is equal to the phase number of electrical machines in the above-mentioned machine drives, which is defined as matched applications in this paper. However, it is possible that the leg number of VSIs may be larger or smaller than the phase number of electrical machines, which is called unmatched applications in this paper. In Refs. [15 – 17], one three-leg VSI is used to control one two-phase load. In Refs. [18 – 20], two three-phase electrical machines are fed by one five-leg VSI. Furthermore,  $(2n + 1)$ -leg VSI is extended to control  $n$  three-phase electrical machines<sup>[21]</sup>. Compared with matched applications, unmatched applications require a smaller leg number. Therefore, unmatched applications can be treated as the fault-tolerant topology of matched applications when some legs of matched applications fail<sup>[19–20]</sup>.

In the matched application, it seems that one phase requires one leg and one leg only can connect one phase, which is the basic idea of the conventional CBPWM. Therefore, the conventional CBPWM cannot be directly used for unmatched applications and necessary modifications are required<sup>[16, 18, 20–21]</sup>. However, the modifications usually depend on the load structure, which reduces the universality of the modified PWM strategy. Besides, the modified CBPWM for unmatched applications can usually be no longer directly utilized for matched applications.

In this paper, a simple but generic PWM strategy is proposed for multi-leg two-level VSI, which is independent from the load structure. The proposed PWM strategy can be directly utilized for both matched and unmatched applications, and no modifications are required.

## 1 Modeling of Multi-Leg VSI

The structure of the  $n$ -leg two-level VSI is illustrated in

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**Biography:** Wang Wei (1985—), male, doctor, lecturer, wangwei1986@seu.edu.cn.

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Fig. 1, in which the structure of the load is not described.

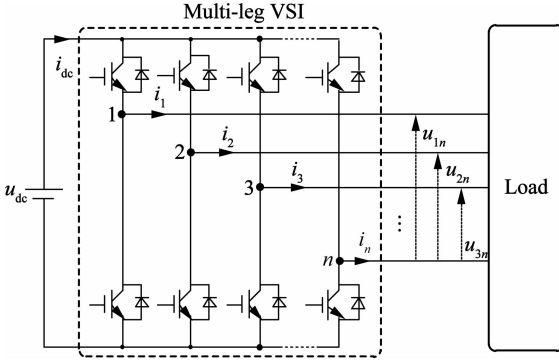


Fig. 1 Structure of the studied system

The leg- $n$  is selected as the reference leg, and the modulated voltage is calculated as

$$u_{kn} = m_{kn} u_{dc} \quad k \in \{1, 2, \dots, n\}, m_{kn} \in [-1, 1] \quad (1)$$

with

$$m_{kn} = \delta_k - \delta_n \quad \delta_k \in [0, 1] \quad (2)$$

where  $u_{kn}$  is the modulated voltage between leg  $k$  and leg  $n$ ;  $u_{dc}$  is the dc-link voltage;  $m_{kn}$  is the modulated ratio between  $u_{kn}$  and  $u_{dc}$ ;  $\delta_k$  is the duty cycle of leg  $k$ . Here,  $u_{nn}$  is a special modulated voltage between leg  $n$  and leg  $n$  and its value is zero. According to Eq. (1), the value of  $m_{nn}$  is also zero.

$u_{dc}$  is delivered to  $n$  modulated voltages by

$$\mathbf{U} = \mathbf{M} u_{dc} \quad (3)$$

with

$$\mathbf{M} = [m_{1n}, m_{2n}, \dots, m_{nn}]^T \quad (4)$$

$$\mathbf{U} = [u_{1n}, u_{2n}, \dots, u_{nn}]^T \quad u_{kn} \in [-u_{dc}, u_{dc}] \quad (5)$$

where  $\mathbf{M}$  is the modulated ratio vector, and  $\mathbf{U}$  is the modulated voltage vector.

## 2 Proposed Modulation Strategy

The task of the proposed PWM strategy is to determine the duty cycle of each leg from the reference modulated voltages. The subscript “ref” is used to identify the reference value of the corresponding variable in this paper.

First, the reference modulated voltage vector  $\mathbf{U}_{ref}$  is obtained from a specific control method. For electrical machines, the control method may be field-oriented control or direct torque control.

Secondly, the modulated ratio vector  $\mathbf{M}$  can be given by inverting Eq. (3):

$$\mathbf{M} = \frac{\mathbf{U}_{ref}}{u_{dc}} \quad (6)$$

with

$$\mathbf{U}_{ref} = [u_{1n\_ref}, \dots, u_{nn\_ref}]^T \quad u_{kn\_ref} \in [-u_{dc}, u_{dc}] \quad (7)$$

where  $u_{kn\_ref}$  is the reference modulated voltage between leg  $k$  and leg  $n$ .

For the  $n$ -leg VSI,  $n$  duty cycles are required to execute voltage commands. According to (2), the duty cycles can be calculated by

$$\left. \begin{aligned} \delta_1 &= m_{1n} + \delta_n \\ \delta_2 &= m_{2n} + \delta_n \\ &\vdots \\ \delta_{n-1} &= m_{(n-1)n} + \delta_n \\ \delta_n &= m_{nn} + \delta_n \end{aligned} \right\} \quad (8)$$

Since  $m_{1n}$ ,  $m_{2n}$ , ...,  $m_{nn}$  have been determined by Eq. (6),  $\delta_1$ ,  $\delta_2$ , ...,  $\delta_n$  only depend on the value of  $\delta_n$ . The problem becomes how to determine the value of  $\delta_n$ .

According to the available value range of duty cycles and ignoring the overmodulation situation, all the duty cycles must satisfy the following conditions:

$$\left. \begin{aligned} \delta_{\min} &= m_{\min} + \delta_n \geq 0 \\ \delta_{\max} &= m_{\max} + \delta_n \leq 1 \end{aligned} \right\} \quad (9)$$

with

$$\left. \begin{aligned} m_{\min} &= \min\{m_{1n}, m_{2n}, \dots, m_{nn}\} \leq 0 \\ m_{\max} &= \max\{m_{1n}, m_{2n}, \dots, m_{nn}\} \geq 0 \end{aligned} \right\} \quad (10)$$

where  $m_{\max}$  and  $m_{\min}$  are the maximum and minimum modulated ratios, respectively;  $\delta_{\max}$  and  $\delta_{\min}$  are the maximum and minimum duty cycles, respectively.

According to (9), the value range of  $\delta_n$  can be determined as

$$-m_{\min} \leq \delta_n \leq 1 - m_{\max} \quad (11)$$

To determine the final value of  $\delta_n$ , (11) is rewritten as

$$\delta_n = -m_{\min} + \eta[1 - (m_{\max} - m_{\min})] \quad (12)$$

where  $\eta$  is the selection coefficient,  $\eta \in [0, 1]$ , which becomes a new freedom degree instead of  $\delta_n$ . Different  $\eta$  will result in different  $\delta_1$ ,  $\delta_2$ , ...,  $\delta_n$ . Furthermore, different duty cycles will result in some different performances. Three different values of  $\eta$  are discussed in this paper:

1) Situation I :  $\eta = 0$

In this situation, all the duty cycles obtain their minimum values, and at least one duty cycle is 0.

2) Situation II :  $\eta = 0.5$

In this situation, all the duty cycles obtain their middle values, and  $1 - \delta_{\max} = \delta_{\min}$ .

3) Situation III :  $\eta = 1$

In this situation, all the duty cycles obtain their maximum values, and at least one duty cycle is 1.

Situation I and Situation III are usually called discontinuous PWM<sup>[22]</sup>, while Situation II is usually called continuous PWM<sup>[22]</sup>. There will be two switching actions during one switching period if the duty cycle is in (0, 1). The discontinuous PWM has lower switching loss

while the continuous PWM has lower harmonics. In this paper, Situation II is selected for the harmonic-reducing purpose. Substituting  $\eta = 0.5$  into Eq. (12) gives

$$\delta_n = 0.5[1 - (m_{\max} + m_{\min})] \quad (13)$$

The flowchart diagram of the proposed PWM strategy is shown in Fig. 2. The input of the proposed PWM strategy is the modulated voltage  $U_{\text{ref}}$ , which depends on the selection of the reference leg. The final output of the proposed PWM strategy is the duty cycle vector  $\delta$  ( $\delta = [\delta_1, \delta_2, \dots, \delta_n]^T$ ), which is outputted to control the  $n$ -leg two-level VSI.

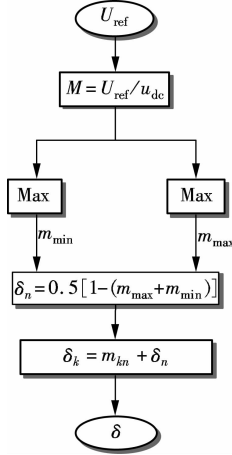


Fig. 2 Flowchart diagram of the proposed PWM strategy

### 3 Universality Analysis

In this section, the universality of the proposed PWM strategy is analyzed by several typical applications.

#### 3.1 Matched application

The typical matched application is that one  $n$ -phase electrical machine is fed by one  $n$ -leg VSI. Here, a five-phase drive system is taken as an example, in which one five-phase electrical machine is fed by one five-leg VSI as shown in Fig. 3. The five-phase electrical machine has five

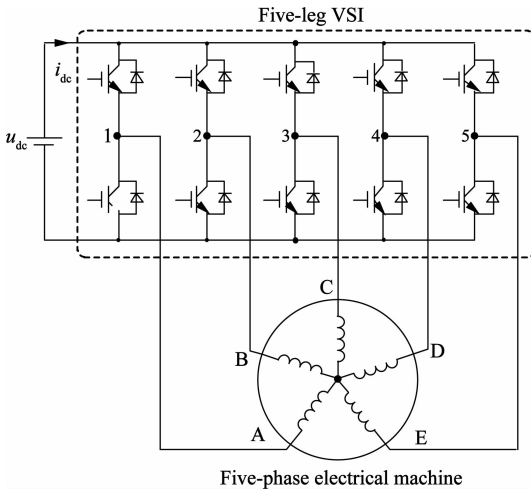


Fig. 3 Example of a matched application

phase windings (phase A, phase B, phase C, phase D, phase E) and the five-leg VSI has five legs (leg 1, leg 2, leg 3, leg 4, leg 5).

According to a specific control method, such as the field-oriented control, the reference phase voltages  $u_{A\_ref}$ ,  $u_{B\_ref}$ ,  $u_{C\_ref}$ ,  $u_{D\_ref}$ , and  $u_{E\_ref}$  can be calculated. To use the proposed PWM strategy, one leg should be selected as the reference leg. Obviously, the five legs are completely the same and any leg can be selected as the reference leg. Here, leg 5 is selected as the reference leg and all reference modulated voltages can be calculated by

$$\left. \begin{aligned} u_{15\_ref} &= u_{A\_ref} - u_{E\_ref} \\ u_{25\_ref} &= u_{B\_ref} - u_{E\_ref} \\ u_{35\_ref} &= u_{C\_ref} - u_{E\_ref} \\ u_{45\_ref} &= u_{D\_ref} - u_{E\_ref} \\ u_{55\_ref} &= 0 \end{aligned} \right\} \quad (14)$$

Based on Fig. 2 and (14), the proposed PWM strategy can be easily used to execute the voltage commands ( $u_{A\_ref}$ ,  $u_{B\_ref}$ ,  $u_{C\_ref}$ ,  $u_{D\_ref}$ ,  $u_{E\_ref}$ ) of the five-phase drive system. Of course, the proposed modulation strategy can be easily extended to any multiphase matched application.

#### 3.2 Unmatched application

According to the proposed PWM strategy, all the modulated voltages should share one same reference leg. If there are  $x$  electrical machines and each electrical machine has  $y$  phase windings, the leg number  $n$  of the VSI can be calculated as

$$n = x(y - 1) + 1 \quad (15)$$

The typical unmatched application is that two three-phase electrical machines (M1, M2) are fed by one five-leg VSI, as shown in Fig. 4. The first electrical machine M1 has three phase windings (A1, B1, C1) while the other three phase windings (A2, B2, C2) belong to the second electrical machine M2. Phase A1, phase B1, phase A2, and phase B2 are connected by leg 1, leg 2, leg 5, and leg 4, respectively. Phase C1 and phase C2

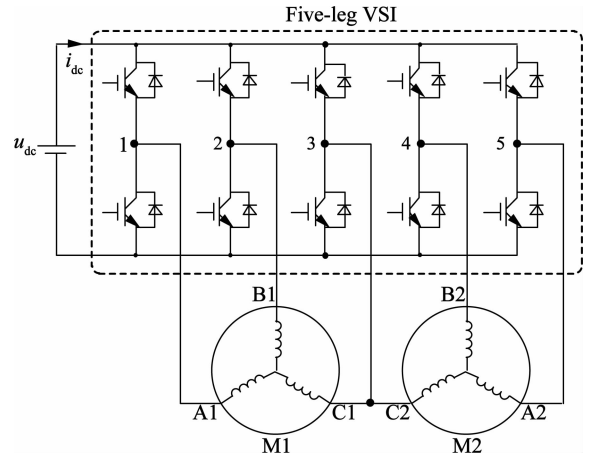


Fig. 4 Example of an unmatched application

share leg 3.

According to a specific control method, such as the field-oriented control, the reference phase voltages ( $u_{A1\_ref}$ ,  $u_{B1\_ref}$ ,  $u_{C1\_ref}$ ,  $u_{A2\_ref}$ ,  $u_{B2\_ref}$ , and  $u_{C2\_ref}$ ) can be calculated. As illustrated in Fig. 4, leg 3 is different from the other four legs and it is the common leg shared by two electrical machines. Compared with the other four legs, leg 3 is a better candidate for the reference leg since the role of the common leg can simplify the calculation of the reference modulated voltages. Therefore, leg 3 is selected as the reference leg and all reference modulated voltages can be calculated by (16). Based on Fig. 2 and (16), the proposed PWM strategy can also be easily used to execute the voltage commands  $u_{A1\_ref}$ ,  $u_{B1\_ref}$ ,  $u_{C1\_ref}$ ,  $u_{A2\_ref}$ ,  $u_{B2\_ref}$ , and  $u_{C2\_ref}$  of the studied unmatched drive system. Similarly, the proposed PWM strategy can be easily extended to any unmatched application.

$$\left. \begin{aligned} u_{13\_ref} &= u_{A1\_ref} - u_{C1\_ref}, u_{23\_ref} = u_{B1\_ref} - u_{C1\_ref} \\ u_{53\_ref} &= u_{A2\_ref} - u_{C2\_ref}, u_{43\_ref} = u_{B2\_ref} - u_{C2\_ref} \\ u_{33\_ref} &= 0 \end{aligned} \right\} \quad (16)$$

## 4 Experimental Validation

To verify the effectiveness of the proposed PWM strategy, an experiment platform is developed, which contains a dSPACE DS1103 controller board and an IGBT-based five-leg VSI. The inputs for the dSPACE DS1103 controller are the measured phase currents and dc-bus voltage, and the feedback signal of the encoder. The switch states for the VSI are generated by the dSPACE DS1103 controller. A personal computer is employed for editing the control program and commanding the dSPACE DS1103 controller. The sampling frequency is 20 kHz. The switching frequencies of matched and unmatched applications are 2 and 10 kHz, respectively.

### 4.1 Experiment of matched applications

To verify the effectiveness of the proposed PWM strategy in matched applications, four RL loads ( $R = 10 \Omega$ ,  $L = 15 \text{ mH}$ ) are used to simulate the multiphase electrical machines from two-phase to four-phase, and the dc bus voltage is set to be 100 V. The detailed experiment platform is illustrated in Fig. 5. The reference phase currents are symmetric sinusoidal waveforms, of which the magnitude and frequency are 1 A and 50 Hz, respectively. All the actual phase currents are measured by current sensors. First, the reference phase currents are compared with the corresponding measured phase currents to generate the reference phase voltages by PI controllers. Then, the reference modulated voltage vector  $U_{ref}$  is obtained by the phase voltage references. According to Fig. 2, the duty cycle vector  $\delta$  can be calculated and outputted to control the multi-leg VSI.

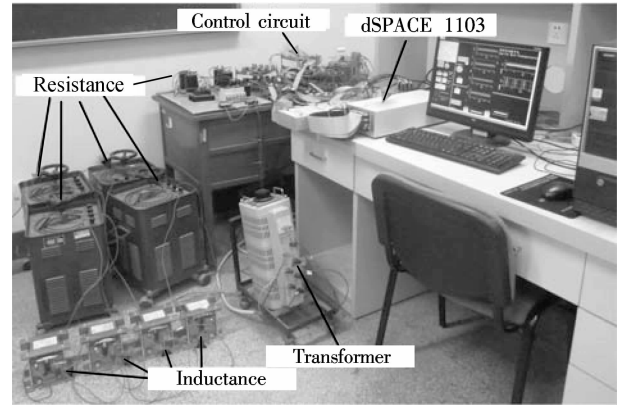


Fig. 5 Experiment platform for matched applications

In this subsection, two-leg, three-leg and four-leg VSIs are deduced from the five-leg VSI to control two-phase, three-phase, four-phase RL loads, and some experiments are carried out. The structures of the three VSIs with different loads and experimental results are illustrated in Figs. 6 to 8, respectively. All the actual currents are very sinusoidal, which can be verified by the smaller THD (total harmonic distortion) of phase currents. Taking Fig. 7 as an example, the THD of phase currents is only 7.07%, which is obtained from the FFT (fast Fourier transformation) analysis. During the three experiments, the proposed PWM strategy can be directly applied without any modifications.

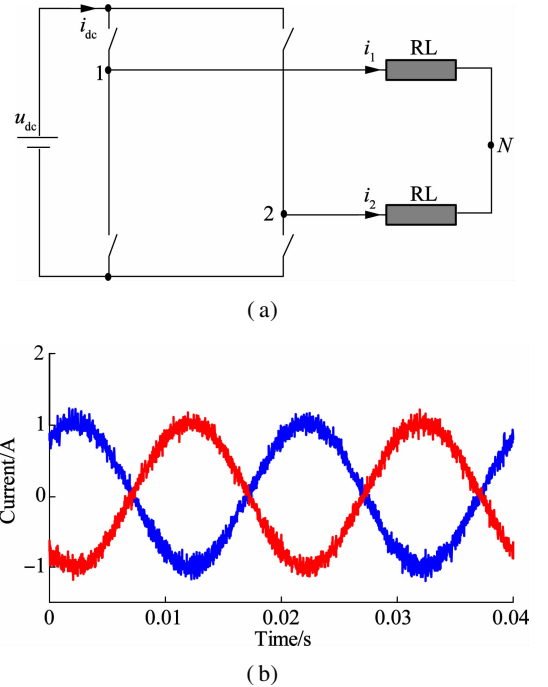
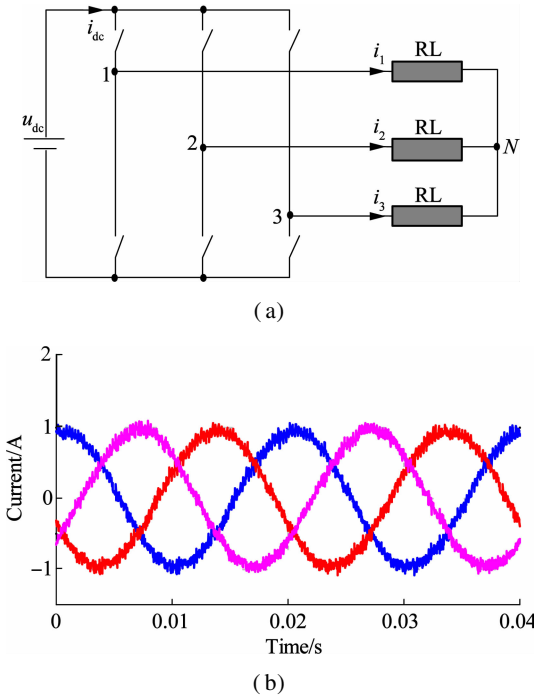


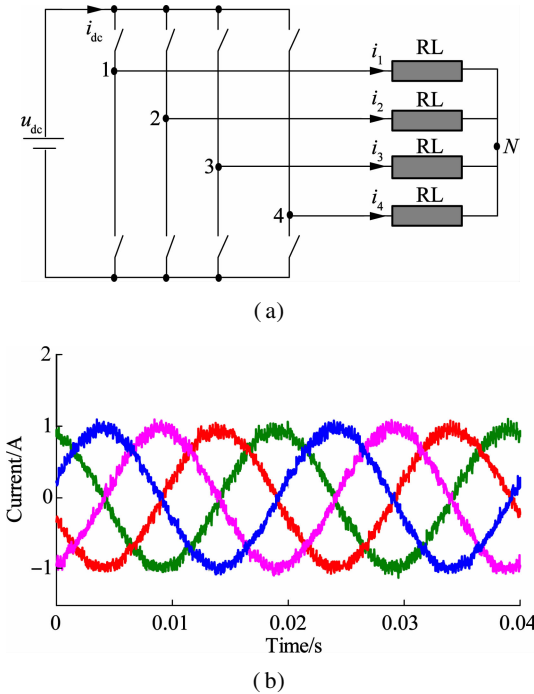
Fig. 6 Two-leg VSI. (a) Structure; (b) Experimental results

### 4.2 Experiment of unmatched application

Fig. 4 is taken as an example of unmatched applications to verify the effectiveness of the proposed PWM strategy in this section, and the detailed experiment platform is

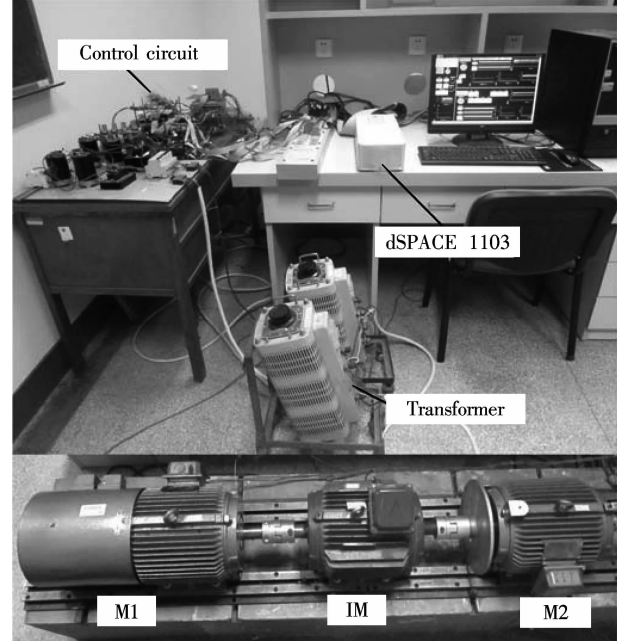


**Fig. 7** Three-leg VSI. (a) Structure; (b) Experimental results



**Fig. 8** Four-leg VSI. (a) Structure; (b) Experimental results

phase currents of M1 and M2 are, respectively, curved in Figs. 10(a) and (b). The current of the common leg (leg 3) is the summation of  $i_{C1}$  and  $i_{C2}$ . The torques of M1 and M2 are, respectively, shown in Figs. 10(d) and (e).



**Fig. 9** Experiment platform for unmatched applications

**Tab. 1** Parameters of PMSM

Parameter	Value
Rated power $P_e$ /kW	5.5
Rated line voltage $U_{lc}$ /V	380
Rated phase current $I_{pc}$ /A	11
Rated speed $n_e$ /rpm	1 500
Stator resistance $R_s$ /Ω	0.665
Stator inductance $L_s$ /mH	7.923
Permanent magnet flux $\psi_{PM}$ /Wb	0.783
Number of pole pairs $p_n$	2
Inertia $J$ /(kg · m <sup>-2</sup> )	0.267 4
Friction factor $\xi$ /(N · m · s)	0.001 6

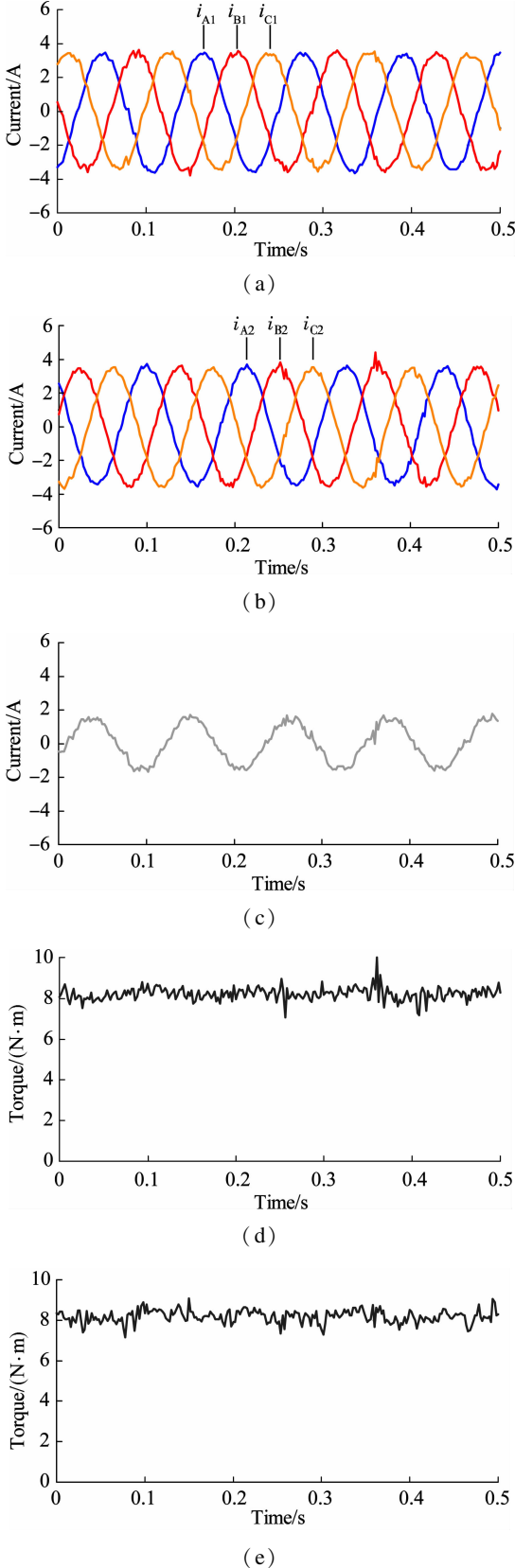
## 5 Conclusion

In this paper, a generic PWM strategy is proposed for multi-leg two-level VSIs, which is based on modulated voltages. Compared with SVPWM, the CBPWM is simpler for multi-leg VSI. As is well-known, the conventional and existing modified CBPWM strategies cannot be directly used for both matched and unmatched applications. However, the proposed PWM strategy is independent from the load structure, and it can be directly used in both matched and unmatched applications. The proposed PWM strategy can be useful for the fast implementation of multi-leg VSI. Therefore, the researchers can concentrate on the development of the control meth-

illustrated in Fig. 9. M1 and M2 are two same permanent magnet synchronous machines (PMSMs) and they are connected by a standard 5.5 kW squirrel-cage induction machine (IM) with an encoder of 1 024 pulses per revolution. The parameters of PMSMs are listed in Tab. 1. The two PMSMs are fed by the five-leg VSI. The drive system is supplied by a 250 V DC bus voltage. The load is realized by the close-loop torque control of the IM using the field oriented control.

The experimental results are illustrated in Fig. 10. The

od for multi-leg VSI since the proposed PWM strategy can be directly used.



**Fig. 10** Experimental results of unmatched applications. (a) Phase current of M1; (b) Phase current of M2; (c) Current of the common leg; (d) Torque of M1; (e) Torque of M2

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## 用于多桥臂电机驱动系统的通用型脉宽调制策略

王 伟 张景皓 程 明

(东南大学电气工程学院, 南京 210096)

**摘要:**提出了一种适用于多桥臂电机驱动系统的通用型脉宽调制策略. 首先,建立不依赖于负载结构的多桥臂逆变器数学模型. 其次,根据多桥臂逆变器的数学模型逆向推导出通用型脉宽调制策略. 根据逆变器桥臂和电机相绕组的数量关系,将电机驱动系统分为匹配和非匹配2种类型. 其中,匹配型电机驱动系统中逆变器桥臂和电机相绕组的数量相等,而非匹配型电机驱动系统中逆变器桥臂和电机相绕组的数量不等. 传统的脉宽调制策略无法直接同时适用于2种不同类型的多桥臂电机驱动系统. 然而,所提的通用型脉宽调制策略可以在不做任何修改的情况下同时适用于2种不同类型的多桥臂电机驱动系统. 最后,实验结果验证了所提通用型脉宽调制策略的有效性.

**关键词:**脉宽调制;多桥臂逆变器;载波型脉宽调制;电机驱动

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