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Improved Zero-Sequence Current Hysteresis Control Based-Space Vector Modulation for Open-End Winding PMSM Drives with Common DC Bus

Zhiping Dong, Zaixin Song, Wusen Wang, and Chunhua Liu, Senior Member

Abstract—Through the zero-sequence current (ZSC) hysteresis controller, the existing ZSC hysteresis control-based space vector modulation (SVM) strategy can provide a satisfactory ZSC suppression effect and greatly reduce the complexity for the open-end winding permanent magnet synchronous machine (OW-PMSM) drive with common dc bus. However, the corresponding linear modulation range is reduced by 12.7% compared with the middle hexagon space vector modulation (MH-SVM) for the OW-PMSM drive. To this end, this letter improves the linear modulation range of the existing strategy. The candidate voltage vectors for each sector are re-selected, and three active voltage vectors will be employed in the extended feasible region. While ensuring the ZSC hysteresis control, the linear modulation range of the proposed strategy is the same as the MH-SVM. At last, experimental results verify the feasibility and effectiveness of the proposed strategy. The proposed strategy can suppress the ZSC effectively, and the corresponding maximum speed is the same as the counterpart of the MH-SVM.

Index Terms—Open-end winding permanent magnet synchronous machine (OW-PMSM), space vector modulation, hysteresis control, zero-sequence current, linear modulation range.

I. INTRODUCTION

An inherent zero-sequence loop exists in the open-end winding permanent magnet synchronous machine (OW-PMSM) drive with common dc bus. The resulting zero-sequence current (ZSC) will lead to the undesired torque ripple and additional power loss. Typically, the PWM switching sequences, the nonlinearity of the inverter, the third harmonic of the back electromotive force (EMF), and even the cross-coupling effect from the machine side will contribute to the zero-sequence voltage generation in the OW-PMSM drive with common dc bus [1-3].

Many researchers have devoted their efforts to suppress the ZSC in open-end winding motor drives. The output zero-sequence voltage (ZSV) of the PWM switching sequence is controlled to be zero in [4, 5], which avoids ZSC generation from the inverter side, but the ZSC from the third harmonic of the back EMF is not controllable. Thus, additional ZSC controller and the corresponding modulation strategy, such as the proportional-resonant controller [2, 3] and predictive controller [6, 7], are employed to suppress the ZSC. However, these strategies suffer from the following problems. First, it is not easy to build an accurate model for the controller. Second, parameter tuning is necessary. Third, the ZSC suppression is affected in the high modulation index range of the α-β subspace. Moreover, they increase the complexity of the drive system. Consequently, a ZSC hysteresis controller is adopted in the OW-PMSM drive [8]. The voltage vectors with non-zero zero-sequence components, which have the opposite polarity to the ZSC, are selected as the basic voltage vectors for the α-β subspace modulation. After α-β subspace modulation, the resulting zero-sequence voltage from the basic voltage vectors is utilized to suppress the ZSC. From the experimental results, it can be seen that the ZSC hysteresis controller can also suppress the ZSC effectively, and the implementation is simpler and more intuitive. Moreover, it does not require the motor parameters, and parameter tuning can be avoided. However, compared with the middle hexagon space vector modulation (MH-SVM) in [5], the ZSC hysteresis control based-SVM (ZHC-SVM) in [8] reduces the linear modulation range simultaneously. It will diminish the advantage of high dc-link voltage utilization in the open-end winding motor drive.

Based on the aforementioned issue, this letter develops an improved ZHC-SVM strategy for the OW-PMSM drive with common dc bus. For each sector, the candidate voltage vectors in one sampling period are updated. Two active voltage vectors and one null voltage vector are employed in the fundamental modulation region, which is the same as the strategy in [8], and three active voltage vectors are employed in the extended modulation region. It extends the linear modulation range to the

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same as the MH-SVM and still keeps the ZSC hysteresis controller with effective ZSC suppression.

II. IMPROVED ZSC HYSTERESIS CONTROL BASED-SVM

The voltage vectors of the two single inverters are marked by 1-8 and 1’-8’, respectively, as depicted in Fig.1(a). Based on the topology of the open-end winding motor drive, the voltage vector distribution of the dual inverter is presented in Fig.1(b). In the case of voltage vector 24’, the voltage vector 2 is produced by the first inverter, and voltage vector 4’ is produced by the second inverter. Other cases are similar. The voltage vectors with positive ZSV and negative ZSV are marked as orange and green, respectively. The whole \( \alpha-\beta \) subspace is divided into six sectors S1-S6.

For the existing ZHC-SVM in [8], one null voltage vector, one active voltage vector without ZSV, and one active voltage vector with ZSV for ZSC hysteresis controller are employed for modulation in one sampling period. Taking sector 1 as an example, while ZSC > 0, negative ZSV is required to suppress it, thus voltage vector 14’ is selected. In order to ensure that the corresponding feasible region completely covers the angle range of sector 1 without affecting the ZSC hysteresis control, the voltage vector 14’ is selected. In order to ensure that the voltage vector 14’ is selected while ZSC > 0, two active voltage vectors without ZSV and one active voltage vector with ZSV are selected while ZSC > 0, two active voltage vectors without ZSV and one active voltage vector with ZSV.

\[
u_{d} = \frac{\Delta P_{eq} + \Delta P_{eq}}{\sqrt{2}} \approx 0.873u_{dc}
\]

For the MH-SVM, voltage vectors at the vertices of hexagon PQRSTU in Fig.1(b) are employed to modulate, and the linear modulation range of the existing ZHC-SVM depends on the intersection of the FFRs in Fig.2(a) and (b), and the limitation circle of the linear modulation range is tangent to both lines AP and BT. Consequently, the radius of the linear modulation range can be derived as

\[
r = \frac{PO \cdot AO}{AP} = 4u_{dc}/\sqrt{21} \approx 0.873u_{dc}
\]

However, the linear modulation range is reduced compared with the MH-SVM in [5]. As depicted in Fig.2(c), the linear modulation range of the existing ZHC-SVM depends on the intersection of the FFRs in Fig.2(a) and (b), and the limitation circle of the linear modulation range is tangent to both lines AP and BT. Consequently, the radius of the linear modulation range can be derived as

\[
r = \frac{PO \cdot AO}{AP} = 4u_{dc}/\sqrt{21} \approx 0.873u_{dc}
\]

To extend the linear modulation range of the existing ZHC-SVM, three active voltage vectors can be applied in one sampling period. Still take sector 1 as an example, while the reference voltage vector is out of the FFR and ZSC > 0, two active voltage vectors without ZSV and one active voltage vector with ZSV can be studied in the same way, and the selected voltage vectors are presented in Table 1, under the columns named “In FFR”. The specific implementation process can refer to [8].
negative ZSV, namely, voltage vectors 35', 24', and 14', can be applied to modulate without the null voltage vector. Thus, the extended feasible region (EFR) \( \Delta \text{APU} \) is obtained, and the whole feasible region becomes the quadrilateral \( \text{AUPO} \), as shown in Fig. 3(a). Moreover, since voltage vector 14' is preserved, the ZSC hysteresis control is still working. The three active voltage vectors (35', 24', and 14' in sector 1, ZSC > 0) can be denoted as \( u_x \), \( u_y \), and \( u_z \), respectively. Meanwhile, since the null voltage vector does not participate in modulation, the duty cycle of the three active voltage vectors can be derived as

\[
\begin{align*}
\frac{u_{ax} d_x + u_{ay} d_y + u_{az} d_z}{d_x + d_y + d_z} &= u_{a_{ref}} \\
\frac{u_{bx} d_x + u_{by} d_y + u_{bz} d_z}{d_x + d_y + d_z} &= u_{b_{ref}} \\
\frac{u_{cx} d_x + u_{cy} d_y + u_{cz} d_z}{d_x + d_y + d_z} &= u_{c_{ref}}
\end{align*}
\]

(3)

In the same manner, voltage vectors 25', 24', and 13' are selected while ZSC ≤ 0 in the EFR \( \Delta \text{BTU} \), and the whole feasible region becomes the quadrilateral \( \text{BUTO} \), as shown in Fig. 3(b). Other sectors can be investigated in the same way, and the selected voltage vectors are presented in Table I, under the columns named “In EFR”. Further, it can be seen in Fig. 3(c) that the intersection of the feasible regions is consistent with the feasible region of the MH-SVM. Therefore, the linear modulation range is re-extended to \( u_{dc} \).

According to the aforementioned analysis, the modulation index can be defined as \( m_{ab} = \left| u_{ap_{ref}} \right| / u_{ref} \), and \( \theta = \arctan \left( u_{b_{ref}} / u_{a_{ref}} \right) \). Based on [8], the ZSC suppression depends on the output ZSV capability of the hysteresis controller, the output ZSV capability of the existing ZHC-SVM in [8] and the improved ZHC-SVM under different \( m_{ab} \) and \( \theta \) can be depicted as Fig. 4 (ZSV > 0). It can be seen that the ZSV output capability of the existing ZHC-SVM in [8] and the improved ZHC-SVM are the same while \( m_{ab} \leq 0.873 \). However, once \( m_{ab} > 0.873 \), it is out of the linear modulation range of the existing ZHC-SVM in [8]. Thus, there is no more ZSV output capability. But for the improved ZHC-SVM, due to the improved linear modulation range, it still can generate ZSV while \( m_{ab} > 0.873 \). The same conclusion can be obtained from the counterpart while ZSV < 0.

For the implementation of the improved ZHC-SVM, there are mainly four steps, as shown in Fig. 5 (a). First, the sector of the reference voltage vector should be determined by \( u_{a_{ref}} \). Second, once the sector is obtained, we can assume that the reference voltage vector is in the FFR, and the candidate voltage vectors are selected from Table I under the columns named “In FFR”. Third, if the sum of the duty cycles for the candidate voltage vectors calculated by (1) is less than one, it means the reference voltage vector is in the FFR, which is the same as the existing ZHC-SVM. If the sum is more than one, it means the reference voltage vector is out of the FFR but in the EFR. Thus, the candidate voltage vectors are selected from Table I under the columns named “In EFR”, and the corresponding duty cycles are calculated by (3). At last, the PWM switching sequence is generated according to the duty cycles of the candidate voltage vectors. The general control diagram of the improved ZHC-SVM strategy for the OW-PMSM drive is depicted in Fig. 5 (b), and it can be seen that the improved ZHC-SVM can work with different controllers for the \( \alpha-\beta \) subspace, and the ZSC is always suppressed by the hysteresis controller.
III. EXPERIMENTAL VALIDATION

To verify the performance of the improved ZHC-SVM strategy, it is experimentally tested on an OW-PMSM drive platform with common dc bus, and a magnetic powder brake is employed to provide the load torque. The dc voltage source is set as 48V, and the sampling frequency is set as 20kHz. For the OW-PMSM, the $d$-axis inductance is 3.7mH, the $q$-axis inductance is 5mH, the zero-sequence inductance is 4mH, and the stator resistance is 0.9Ω. It has 5 pole pairs with a rotor flux linkage of 0.055Wb. In addition, the third harmonic component of the rotor flux linkage is 0.001Wb. Under the 48V dc-link voltage, the rated speed and torque are 1000r/min and 2N·m, respectively.

Five different control methods are compared in the experiment. They adopt the same deadbeat controller for the $\alpha$-$\beta$ subspace in the OW-PMSM drive, but their modulation strategy and ZSC control are not the same. For Method I, only MH-SVM is applied, and there is no more ZSC treatment, employed as the blank benchmark method. It is utilized to verify the necessity of the ZSC suppression and present the suppression effect of other methods. For Methods II and III, MH-SVM is still applied in the $\alpha$-$\beta$ subspace modulation, and voltage vectors 78' and 87' are applied to provide ZSV. To control the ZSC, a deadbeat controller is adopted in Methods II, and a PI controller is adopted in Methods III. For Methods IV, alternate sub-hexagonal center PWM (ASHC-PWM) in [4] is applied, and ZSC is also suppressed by voltage vectors 78' and 87' coupled with the PI controller. Besides, Method V adopts the existing ZHC-SVM in [8]. Method VI adopts the improved ZHC-SVM in this letter. Meanwhile, no flux-weakening or overmodulation algorithms are added, and the reference voltage vector is limited to the linear modulation range.

A. ZSC Suppression Test

First, the ZSC ($i_0$ in the figures) suppression effect of the five methods is compared at 500r/min and 1000r/min with 2N·m load. As shown in Fig.6(a) and Fig.7(a), Method I cannot suppress the ZSC since it has no active control of the ZSC from the third harmonic rotor flux linkage. The ZSC ripples (peak to peak) are 2.05A and 1.27A, and the corresponding THDs are 16.36% and 9.41%, respectively. For the FFT analysis of the phase current, ZSC mainly contributes to the dc and the third harmonic components. It means that the undesired ZSC will greatly degrade the current performance of the OW-PMSM and should be suppressed well. On the contrary, as shown in Fig.6(b)-(e), Methods II-VI can all suppress the ZSC effectively at 500r/min since they control the ZSC actively. The ZSC ripples are all suppressed to less than 0.7A, and the THDs are all about 3.6%.

However, under 500r/min test in Fig. 6, it is noteworthy that the deadbeat and PI controllers in Methods II, III, and IV (ZSC ripple: 0.58A, 0.63A, and 0.55A) do not show a clear advantage in ZSC suppression compared with the hysteresis controller in Methods V and VI (ZSC ripple: 0.66A and 0.67A). Thus, through the simple hysteresis controller, the ZSC could also be suppressed well. A similar conclusion can also be obtained from the 1000r/min test in Fig. 7. Moreover, Method VI (ZSC ripple: 0.68A) even has a better ZSC suppression effect at 1000r/min compared with Methods II, III, and IV (ZSC ripple: 0.92A, 0.85A, and 0.80A). It is because Methods II, III, and IV do not have enough remaining switching period for ZSV in the high modulation index range, but Method VI still can generate ZSV in the high modulation index range owing to different candidate voltage vector selection. In addition, Method V is not tested at 1000r/min, since 1000r/min speed operation is out of the linear modulation range of Method V, which will be further discussed in the following part.
Besides, ZSC hysteresis controller does not depend on motor parameters, and avoids parameter tuning. Compared with deadbeat or PI controllers, ZSC hysteresis controller is simpler and easier to realize. As shown in Fig. 8, Method II is sensitive to the parameter mismatch, especially the zero-sequence inductance. Under 50% zero-sequence inductance mismatch, the ZSC ripple increases to 0.99A. For Method III, the ZSC suppression effect of the PI controller highly depends on the proportional coefficient. Improper coefficients will lead to significantly worse suppression effect. However, for the ZSC hysteresis controller in Methods V and VI, the ZSC ripple can be suppressed to about 0.65A. It does not depend on motor parameters or require parameter tuning, which is the main advantage of the proposed ZHC-SVM.

IV. Conclusion

In this letter, an improved ZHC-SVM strategy is proposed for the OW-PMSM drive with common dc bus. Based on the existing ZHC-SVM strategy for the OW-PMSM drive with common dc bus, the candidate voltage vectors for each sector are re-selected, and three active voltage vectors will be employed in the extended feasible region. Thus, the linear modulation range of the improved ZHC-SVM is re-extended to be the same as the MH-SVM, and the hysteresis controller for the ZSC is still preserved. From the experimental results, it can be found that the improved ZHC-SVM can provide a satisfactory ZSC suppression effect under different speed ranges, and the maximum speed is the same as the counterpart of the MH-SVM.

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