Reference voltage vector based model predictive control for semicontrolled open-winding flux-switching permanent magnet generator system with a novel zero-sequence current suppression strategy

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Abstract
This paper studies a reference voltage vector (RVV) based model predictive control (MPC) for semicontrolled open-winding flux-switching permanent magnet generator (SOW-FSPMG). Common dc bus is adopted in this configuration, thereby leading to zero-sequence current (ZSC). The first concern of this work is put into proposing a novel ZSC suppression strategy, which is on the basis of the redundant vector pre-selection. Secondly, a deadbeat flux control (DBFC) is adopted to calculate the RVV. Then, only 4, 3 or 2 vectors adjacent to the RVV are of interest during each sampling period, thereby decreasing the computation burden; meanwhile, a simplified cost function that evaluates the error between the RVV and the prediction voltage vectors is defined. Thirdly, the side effect of dead-time inherent to voltage source converter (VSC) on the system’s steady-state performance is analysed and discussed. In order to properly leverage the dead-time, a solution to regulate duty-cycles of the dead-time voltage vector and the selected one is studied, by which means, steady-state performance of the system can be highly improved. Finally, experimental results are presented to verify the correctness and effectiveness of the proposed method.

1 | INTRODUCTION

Nowadays, due to the environmental-friendly feature, wind energy has been actively developed [1–3]. The permanent magnet synchronous generator (PMSG) is widely employed in wind power generation systems owing to its high power density, flexible magnet topologies, and excellent operation performance [4, 5]. Compared to traditional permanent magnet (PM) generators, flux-switching permanent magnet generator (FSPMG) is more favourable for the wind power generation system, which is especially owing to its stator PM structure and hence the capacity of anti-demagnetization [6, 7].

In addition, with the power capacity growth of wind power generation, open-winding (OW) generation system has received ever increasing concern because of its interesting merits like good fault tolerance ability, flexible control objective, and multilevel modulation effect. In this configuration, the machine is re-constructed by purposely disconnecting the neutral point and powered by an additional voltage source converter (VSC) along with the original VSC. However, the additional VSC inevitably complicates the system and increases the overall cost to some extent. In view of these drawbacks, a PMSG-based semicontrolled OW (SOW) generation system is proposed in [8]. The additional VSC is superseded by a three-phase diode bridge, and therefore the complexity of the system can be significantly reduced. In this paper, the SOW configuration incorporating FSPMG is investigated and it is called SOW-FSPMG.

Similar to the conventional OW system, SOW-FSPMG can be with a single or two isolated dc bus supplies as well. The SOW-FSPMG with a common dc bus provides convenient implementation over its dual dc bus counterpart in practical
applications, since the common voltage and the bearing current are negligible, as discussed in [9, 10]. Nevertheless, applying common dc bus will result in the problem of zero-sequence current (ZSC), inevitably decreasing the system efficiency [11, 12]. Therefore, a plenty of methods have been presented to suppress the ZSC.

In [13], a decoupled space-vector-based pulse width modulation (PWM) strategy is reported and applied to OW induction machine (IM) drive system, and the ZSC is suppressed by eliminating the zero sequence voltage (ZSV) for both converters. This ZSC suppression strategy is extended to five-phase OW IM drive in [14]. Furthermore, the SOW configuration combining PMSG is investigated in [15], where the traditional PI controller is replaced by the proportional resonant controller, whereas the ZSC suppression is achieved by means of ZSV elimination as well.

Dissimilarly, a finite-control-set model predictive torque control (FCS-MPTC) method is developed and employed in OW IM system, in which, the ZSC along with output torque and stator flux are constrained in the cost function [16]. Weighting factors are required to make a trade-off between ZSC and other variables. However, the tuning work of weighting factors is a time-consuming task due to the absence of theoretical support. In view of this drawback, a finite-control-set model predictive flux control (FCS-MPFC) algorithm is proposed in [17], where both the stator current and the ZSC are transformed into stator flux vector so that no additional weighting factor is required. In particular, as mentioned in [18, 19], the existence of third harmonic back electromotive force (EMF) in PMSG or IM significantly results in the low-order harmonic ZSC. Fortunately, the back EMF waveform of FSPMG is highly sinusoidal owing to the complementary structure in windings, thus the third harmonic no longer comes into existence. From this fact, the effect of third harmonic on the ZSC is not under consideration in this work.

Besides, it should be noted that in order to prevent short circuit of dc-bus of VSC, arranging a proper dead-time between up and down insulated gate bipolar transistor (IGBT) of one bridge is indispensable, regardless of the control method. But, the dead-time inevitably causes an error of output voltage and distorts stator current. At present, various improved PWM control methods have been proposed to overcome the side effect of dead-time [20–22]. In principle, these methods are to directly prolong or shorten the gating pulse widths within each switching cycle according to the load current direction.

Nevertheless, owing to different mechanisms for applying voltage vector, the dead-time effect when finite-control-set model predictive control (FCS-MPC) method is used is quite different from that for PWM control methods. Up to present, only few literature places emphasis on studying dead-time effect of FCS-MPC method. In [23], an FCS-MPC-based direct power control method incorporating dead-time effect compensation is proposed for grid-tie three-level neutral point clamped inverter.

In this method, the dead-time effect is considered in the prediction model. Besides the effect of dead-time on common-mode voltage is studied in [24], where the cost function includes a term of common-mode voltage so that the effect of dead-time can be mitigated to some extent.

Above methods are to passively compensate the dead-time, and accordingly to enhance steady-state performance. However, this passive compensation is not an optimal strategy definitely because the dead-time could assist improving the steady-state performance under some conditions. In fact, the switching pattern of inverter during the dead-time also provides a voltage vector though its duration is very short. This vector is called dead-time vector in what follows. In [25], an optimized FCS-MPC method considering utilization of dead-time vector to improve steady-state performance is proposed for two-level inverter-fed permanent magnet synchronous motor (PMSM) drives. In this method, the dead-time vector is leveraged and inserted along with the selected vector at one sampling period, so as to avoid the side effect of dead-time vector while to improve the steady-state performance to some extent. However, a simply inherited application of this optimized FCS-MPC method in SOW-FSPMG system is no longer attractive and feasible. This is so since that voltage vectors of SOW-FSPMG system depend on not only switching patterns of VSC but currents’ polarities as well, highly complicating the calculation of dead-time vector duration.

In this paper, the problem of ZSC along with the dead-time inherent to converter is addressed. In particular, a novel ZSC suppression strategy is proposed, which is based on the redundant vector pre-selection. By the proposed strategy, not only introducing additional weighting factor [16] is avoided but also complicating the cost function [17] is not required. In addition, a deadbeat flux control (DBFC) method is adopted to obtain an RVV, by which, the number of prediction vectors is highly reduced and thus the computation burden reduction is achieved. Besides, a solution based on the insertion of dead-time vector along with the selected vector is developed, which is for the sake of alleviating the side effect of dead-time and therefore improving the steady-state performance of the system.

The rest of the paper is organized as follows. In Section 2, the SOW-FSPMG system is introduced. Next, Section 3 details the proposed RVV-based MPC method. The proposed method is tested by experiments in Section 4. Finally, Section 5 concludes this paper.

2 | TOPOLOGY AND MATHEMATICAL MODEL

2.1 | Topology and features of the FSPMG

A three-phase 12/10-pole FSPMG is tested, and its topology is shown in Figure 1. The rotor is composed of salient laminations with neither permanent magnets nor windings, which is simple in structure and suitable for high-speed operation. The stator consists of 12 segments of “U”-shaped magnetic cores, and 12 pieces of magnets are sandwiched between each pair of magnetic cores and magnetized circumferentially in alternative opposite directions. In addition, the concentrated windings are
employed, which are wound around two adjacent stator teeth with a piece of magnet in the middle, leading to low copper consumption and low copper loss due to short end windings. The 12 coils are divided into three groups, and each four coils belonging to one group is connected in series to form one phase.

Figure 2(a) shows the tested machine's back EMF waveform at no load under rated speed (1500 rpm), which is obtained by virtue of finite-element method. It can be seen that the amplitude of the back EMF is 263 V, and the waveform is highly symmetrical. The corresponding fast Fourier transform (FFT) result is presented in Figure 2(b), from which, it is seen that the total harmonic distortion is merely 1.5%. Meanwhile, due to the complementary structure of the machine, the third harmonic component is absent, while higher order harmonic components are negligible and mainly composed of 5th and 7th. Neglecting the higher order harmonics, three-phase back EMFs can be expressed as:

$$\begin{align}
e_a &= E_m \sin(\omega t) \\
e_b &= E_m \sin(\omega t - \frac{2\pi}{3}) \\
e_c &= E_m \sin(\omega t + \frac{2\pi}{3})
\end{align}$$

(1)

where $\omega$ is the rotor electric angle speed; $E_m$ is the amplitude of the fundamental back EMF.

2.2 Mathematical model of the SOW-FSPMG system

Three-phase SOW-FSPMG system with a common dc bus is illustrated in Figure 3, where $u_{dc}$ represents the dc bus voltage. The conventional star-connected neutral point of the machine is disconnected, then a three-phase diode bridge along with a three-phase VSC is employed to power the SOW-FSPMG.

The corresponding equivalent circuit is shown in Figure 4. In the stationary reference frame, three-phase voltages of SOW-FSPMG can be described as,

$$\begin{bmatrix}
u_a \\
u_b \\
u_c
\end{bmatrix} = \frac{1}{3} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L
\end{bmatrix} \begin{bmatrix} i_a \\
i_b \\
i_c
\end{bmatrix} + \begin{bmatrix} e_a \\
e_b \\
e_c
\end{bmatrix} - R \begin{bmatrix} i_a \\
i_b \\
i_c
\end{bmatrix}$$

(2)
where \( n_k \) and \( i_k \) \((k = a, b \text{ or } c)\) represent phase stator voltage and phase current, respectively; \( R \) is the stator resistance; \( L \) is the stator winding self-inductance; \( M \) is the stator winding mutual inductance; \( u_{a1}, u_{b1} \) and \( u_{c1} \) are the ac-side voltages of VSC; \( u_{a2}, u_{b2} \) and \( u_{c2} \) are the ac-side voltages of diode bridge.

Furthermore, the ac-side voltages of VSC are decided by the state of switching devices and governed by,

\[
\begin{align*}
    u_{a1} &= S_{a1} u_{dc} \\
    u_{b1} &= S_{b1} u_{dc} \\
    u_{c1} &= S_{c1} u_{dc}
\end{align*}
\]

(3)

where \( S_{k1} \) \((k = a, b \text{ or } c)\) denotes the switch function of the bridge arm in VSC. \( S_{k1} = 1 \) \((0)\) means the upper (or lower) switch is ON.

Moreover, different from VSC, ac-side voltages of the diode bridge are determined by the polarities of phase currents, respectively:

\[
\begin{align*}
    u_{a2} &= \left[1 - \text{sgn} \left( i_a \right) \right] \cdot u_{dc} / 2 \\
    u_{b2} &= \left[1 - \text{sgn} \left( i_b \right) \right] \cdot u_{dc} / 2 \\
    u_{c2} &= \left[1 - \text{sgn} \left( i_c \right) \right] \cdot u_{dc} / 2
\end{align*}
\]

(4)

where the sign function \( \text{sgn}() \) can be specially expressed as:

\[
\text{sgn} \left( i_k \right) = \begin{cases}
    1, & (i_k > 0) \quad k = a, b, c \\
    -1, & (i_k < 0)
\end{cases}
\]

(5)

Additionally, according to Equations (2), (3), and (4), the voltage vector \( u_i \) \((i = 0, 1, 2, \ldots 6)\) generated by VSC and \( u_j \) \((j = 1, 2, \ldots 6)\) generated by diode bridge can be expressed in the \( \alpha \beta 0 \) plane as:

\[
u_i = \frac{2}{3} \left( S_{a1} + S_{b1} e^{\frac{2\pi}{3}} + S_{c1} e^{\frac{4\pi}{3}} \right) u_{dc}
\]

(6)

\[
u_j = \frac{1}{3} \left[ 1 - \text{sgn} \left( i_a \right) \right] + \left[ 1 - \text{sgn} \left( i_b \right) \right] e^{\frac{2\pi}{3}} + \left[ 1 - \text{sgn} \left( i_c \right) \right] e^{\frac{4\pi}{3}} u_{dc}
\]

(7)

The VSC can form eight voltage vectors, including six non-zero voltage vectors and two zero voltage vectors, as shown in Figure 5(a). Whereas, due to the fact that the three-phase currents are never of the same polarity simultaneously, only six rather than eight voltage vectors are available for the uncontrollable diode bridge, as presented in Figure 5(b). Table 1 depicts the relationship between voltage vectors and the polarities of phase currents in diode bridge, in which “+” and “−” represent positive current and negative current, respectively.

As shown in Figure 4, in the SOW-FSPMG system with a common dc bus, the ZSC can be induced due to the zero-sequence path. The zero sequence component is therefore under consideration, and the voltage model of the SOW-FSPMG in the \( dq0 \) plane should be further described as,

\[
\begin{bmatrix}
    n_d \\
    n_q \\
    n_0
\end{bmatrix} = \begin{bmatrix}
    -L_d & 0 & 0 \\
    0 & -L_q & 0 \\
    0 & 0 & -L_0
\end{bmatrix} \begin{bmatrix}
    i_d \\
    i_q \\
    i_0
\end{bmatrix} + \begin{bmatrix}
    -R \omega L_d & 0 & 0 \\
    0 & -R \omega L_q & 0 \\
    0 & 0 & -R
\end{bmatrix} \begin{bmatrix}
    i_d \\
    i_q \\
    i_0
\end{bmatrix}
\]

(8)

with

\[
\begin{align*}
    n_0 &= \left( S_{a1} + S_{b1} + S_{c1} \right) - \left( S_{a2} + S_{b2} + S_{c2} \right) u_{dc} / 3 \\
    i_0 &= (i_a + i_b + i_c) / 3
\end{align*}
\]

(9)

where the subscripts \( d, q \) and \( 0 \) mean the components in \( dq0 \) plane, respectively; \( S_{a2}, S_{b2} \) and \( S_{c2} \) rely on the phase current polarities of the diode bridge. For instance, \( S_{a2} = 1 \) means that the phase current \( i_a \) is negative, while \( S_{b2} = 2 \) means that \( i_b \) is positive. \( L_0 = L - 2M \) represents zero-sequence inductance [20]; \( \Psi \) is the amplitude of PM flux linkage.
2.3 Basic voltage vector analysis

The basic voltage vector (BVV) $V_{ij}$ available in the SOW-FSPMG system can be obtained by synthetic vector equation, namely the voltage vector of the VSC minus that in the diode bridge, as:

$$V_{ij} = u_i - v_j$$  (10)

For each current polarity, there are eight BVVs, which are dependent on the switching states of VSC, to be obtained, as depicted in Figure 6. For instance, if phase current $i_a$ and $i_b$ are positive, whereas $i_c$ is negative, $r_3$(001) of the uncontrollable side is determined and it corresponds to vector $OM$, as shown in Figure 6. Placing “-” in front of $r_5$, vector $OF$ is derived. According to Equation (10), the original hexagon shown in Figure 5(a) should pan, along the direction of vector $OF$, to the hexagon OABCDE centred on point $F$. In the case of other current polarities, BVVs can be acquired in the same manner.

3 PRINCIPLE OF PROPOSED METHOD

To overcome the ZSC along with the dead-time inherent to converter in SOW-FSPMG, an RVV-based MPC method incorporating a novel ZSC suppression strategy is proposed. The corresponding control diagram is illustrated in Figure 7. There are five key parts to be implemented: the redundant vector pre-selection, the RVV calculation, the optimal voltage vector selection, the dead-time vector judgement, and the dead-time calculation. Below sub-sections detail these parts, followed by a particular sub-section to summarize the proposed method.

3.1 Novel ZSC suppression strategy

In conventional FCS-MPTC method for OW system, the ZSC is constrained in the cost function, together with torque and stator flux [16]. In this case, two weighting factors should be introduced to make a trade-off among three variables. However, the tuning of weighting factors (especially more than two) is currently an arduous task due to the lack of advanced theoretical analysis. In order to tackle this problem, a novel ZSC suppression strategy is proposed and discussed in this sub-section.

As can be seen from the mathematical model presented in Equations (8) and (9), non-zero ZSV directly causes ZSC. From this fact, influence of different BVVs on the ZSV should be analysed. The term corresponding to zero sequence component in Equation (8) is discretized by using Euler method, as:

$$i_0(k + 1) = \left(1 - \frac{T_s R}{L_0}\right) i_0(k) - \frac{T_s}{L_0} n_0(k)$$  (11)

where $i_0(k)$ and $n_0(k)$ are ZSC and ZSV at $k$th instant, respectively; $i_0(k+1)$ is ZSC at $(k+1)$th instant; $T_s$ is the sampling period. Accordingly, the zero-sequence equivalent circuit of the SOW-FSPMG system could be obtained as shown in Figure 8.

From Equation (11), if one ZSV $n_0(k)$ is applied to the VSC, the ZSC would vary from $i_0(k)$ in current control period to $i_0(k+1)$ in next control period. In addition, it can be easily found that the coefficient of $n_0(k)$ is negative by nature. Combined with RL circuit characteristics, it can be concluded that ZSC will decrease/increase if ZSV is positive/negative.

Taking the case that $r_5$ is activated from the diode bridge (i.e. the currents’ polarities are $+++$) as an example, Figure 9 shows eight resulting BVVs ($V_{55}$, $V_{15}$, $V_{25}$, ... $V_{75}$) synthesized in this case, and the corresponding ZSVs, $n_0$, are listed in Table 2. It concludes that zero BVV ($V_{55}$) and medium BVVs ($V_{15}$, $V_{35}$) don’t contribute to the production of ZSV and hence the generation of ZSC. In addition, $V_{25}$, $V_{45}$ and $V_{65}$ lead to the same effect on ZSV and hence ZSC. The remaining two vectors, $V_{05}$ and $V_{75}$, are of redundance due to the same amplitudes of $ab$ plane, as depicted in Figure 9. While, they obviously cause opposite effects on the ZSC. This feature is developed to suppress the ZSC.

Table 3 lists the influences of redundant vectors on the ZSC under different current polarities. It concludes that $V_{01}$, $V_{02}$, $V_{03}$, $V_{04}$, $V_{05}$, and $V_{06}$ up the amplitude of ZSC, whilst $V_{21}$, $V_{23}$, $V_{44}$, $V_{74}$, and $V_{76}$ cause the inverse consequence. A further conclusion is that, from the VSC perspective, the employment of $n_0(000)$ will increase the ZSC, whilst applying $n_0(111)$ will decrease the ZSC. In this sense, for suppressing the ZSC without sacrificing the control of stator currents, a rather straightforward solution is the appropriate alternation between these two redundant vectors. To be precise, if $i_0 > 0$, all the
vectors associated with \( u_0 \), namely \( V_{00} \), will be omitted from consideration in the following implementation; and inversely, when \( i_0 < 0 \), all the vectors corresponding to \( u_0 \), namely \( V_{00} \), will be neglected. It is expected that the ZSC is always suppressed as long as the vectors saved from six pairs of redundant vectors is applied.

### 3.2 RVV calculation

By the foresaid ZSC suppression strategy, an optimum voltage vector could be selected from the remaining seven BVVs. Nevertheless, assessing seven candidates is still time-consuming. As such, the solution of DBFC is adopted to calculate the desired RVV, which will be included as the reference in the cost function to evaluate the feasible prediction vectors. Combining machine flux linkage equation and the Euler formula, Equation (8) can be re-expressed as,

\[
\begin{align*}
    u_d(k) &= -R_d i_d(k) + \frac{1}{T_s} (\psi_d(k+1) - \psi_d(k)) - \omega \psi_q(k) \\
    u_q(k) &= -R_q i_q(k) + \frac{1}{T_s} (\psi_q(k+1) - \psi_q(k)) + \omega \psi_d(k)
\end{align*}
\]

(12)

where \( i_d(k)/i_q(k) \) and \( u_d(k)/u_q(k) \) are \( d/q \)-axis current and voltage at \( k \)th instant, respectively; \( \psi_d(k)/\psi_q(k) \) and \( \psi_d(k+1)/\psi_q(k+1) \) are \( d/q \)-axis stator flux linkages at \( k \)th and \( (k+1) \)th instant, respectively.

According to the principle of DBFC principle, the following constraints should be satisfied:

\[
\begin{align*}
    \psi_d(k+1) &= \psi_d^{ref} \\
    \psi_q(k+1) &= \psi_q^{ref}
\end{align*}
\]

(13)

where \( \psi_d^{ref} \) and \( \psi_q^{ref} \) represent \( dq \)-axes components of the stator flux linkage reference, respectively.

The phase differential of the stator flux linkage vector \( \psi \) with respect to \( d \)-axis is commonly defined as load angle \( \delta \), and the current control scheme \( i_d^{ref} = 0 \) is usually employed to minimize copper loss in a manner where the phase difference between the waveforms of stator current and back electromotive force is controlled to be zero. Then, the stator flux linkage amplitude
TABLE 2  BVVs distribution in the case of $i_d > 0$, $i_q > 0$ and $i_r < 0$

| BVVs | $u_x$ | $u_y$ | $u_0$ |
|------|------|------|------|
| $V_{05}$ | $u_{dc}/3$ | $\sqrt{3}u_{dc}/3$ | $-u_{dc}/3$ |
| $V_{15}$ | $u_{dc}$ | $\sqrt{3}u_{dc}/3$ | 0 |
| $V_{25}$ | $2u_{dc}/3$ | $2\sqrt{3}u_{dc}/3$ | $u_{dc}/3$ |
| $V_{35}$ | 0 | $2\sqrt{3}u_{dc}/3$ | 0 |
| $V_{45}$ | $-u_{dc}/3$ | $\sqrt{3}u_{dc}/3$ | $u_{dc}/3$ |
| $V_{55}$ | 0 | 0 | 0 |
| $V_{55}$ | $2u_{dc}/3$ | 0 | $u_{dc}/3$ |
| $V_{55}$ | $u_{dc}/3$ | $\sqrt{3}u_{dc}/3$ | $2u_{dc}/3$ |

TABLE 3  Influence of redundant vectors on the ZSC under different current polarities

| Current polarities ($i_d$, $i_q$, $i_r$) | Redundant vectors | ZSV | Influence on ZSC |
|--------------------------------------|------------------|-----|------------------|
| $+++$ | $V_{05}$ | $-u_{dc}/3$ | up |
| | $V_{15}$ | $2u_{dc}/3$ | down |
| $-++$ | $V_{05}$ | $-u_{dc}/3$ | up |
| | $V_{15}$ | $u_{dc}/3$ | down |
| $--++$ | $V_{45}$ | $-u_{dc}/3$ | up |
| | $V_{55}$ | $2u_{dc}/3$ | down |
| $-+++$ | $V_{45}$ | $-u_{dc}/3$ | up |
| | $V_{55}$ | $u_{dc}/3$ | down |
| $+++-$ | $V_{55}$ | $-u_{dc}/3$ | up |
| | $V_{55}$ | $2u_{dc}/3$ | down |
| $-++-$ | $V_{55}$ | $-u_{dc}/3$ | up |
| | $V_{55}$ | $u_{dc}/3$ | down |

Reference $\psi^*_e$ can be obtained as:

$$\psi^*_e = \sqrt{\psi_e^2 + \left(\frac{2T_e^* I_q^*}{3n_p \psi_f^*}\right)^2}$$  \hspace{1cm} (14)

where $n_p$ is the number of rotor pole; $T_e^*$ is the reference of electromagnetic torque, which can be acquired as:

$$T_e^* = \frac{3}{2} n_p \psi_f I_q^*$$  \hspace{1cm} (15)

where $I_q^*$ is the reference of $q$-axis current, which can be acquired by the outer loop PI controller.

Then, the $dq$-axes components of the stator flux reference can be expressed as:

$$\begin{align*}
\psi^* _d &= \psi^*_e \cos \delta^*_e \\
\psi^* _q &= \psi^*_e \sin \delta^*_e 
\end{align*}$$  \hspace{1cm} (16)

with

$$\delta^*_e = \arcsin \left(\frac{-2T_e^* I_q^*}{3n_p \psi_f^*}\right)$$  \hspace{1cm} (17)

where $\delta^*_e$ is the reference of load angle.

Substituting Equation (13) into (12), the $dq$-axes components of the RVV can be expressed as:

$$\begin{align*}
\psi^*_d &= -Ri_d(k) + \frac{1}{T_s} \left(\psi^*_d - \psi_d(k)\right) - \omega \psi_d(k) \\
\psi^*_q &= -Ri_q(k) + \frac{1}{T_s} \left(\psi^*_q - \psi_q(k)\right) + \omega \psi_d(k)
\end{align*}$$  \hspace{1cm} (18)

By transforming the RVV in Equation (18) into the $\alpha\beta$ plane using the anti-Park's transformation, the RVV $\psi^*_{\alpha\beta}$ can be obtained:

$$\begin{align*}
\psi^*_{\alpha\beta} &= \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \psi^*_d \\ \psi^*_q \end{pmatrix} \\
\psi^*_\alpha &= \psi^*_\alpha^* + j\psi^*_\beta^*
\end{align*}$$  \hspace{1cm} (19)

Subsequently, the position of the RVV in the $\alpha\beta$ plane can be acquired by:

$$\theta^* = \arctan \left(\frac{\psi^*_\beta}{\psi^*_\alpha}\right)$$  \hspace{1cm} (21)

Then, as illustrated in Figure 6, the whole $\alpha\beta$ plane is divided into 12 sectors, and the prediction vectors can be readily determined according to the spatial position of RVV. For example, supposing that the voltage vector activated in diode bridge side is $V_{05}$ (i.e. the currents' polarities are $+++$), and that the polarity of the ZSC at the instant is positive, the closest BVVs are $V_{25}$, $V_{35}$, $V_{55}$ and a pair of redundant vectors $V_{05}$ and $V_{75}$, when $\psi^*_e$ locates in the Sector 3. Meanwhile according to Table 3, $V_{05}$ can be pre-dismissed, so for this case, the number of prediction vectors is 4. Similarly, if $\psi^*_e$ is in Sector 4 or 5, the number of prediction vectors is 3 ($V_{35}$, $V_{45}$, and $V_{55}$) or 2 ($V_{45}$, and $V_{55}$). For other cases, prediction vectors can be determined in the same manner. The number of prediction vectors is degraded to be fewer than five, and hence the computation burden reduction is achieved.

3.3  Cost function

Based on the above formula derivation and theoretical analysis, a simple cost function is designed to evaluate the error between the amplitude of the RVV and prediction vectors, which is expressed as:

$$g = \left|\psi^*_d - V^*_{\alpha_d}\right| + \left|\psi^*_q - V^*_{\alpha_q}\right|$$  \hspace{1cm} (22)
where $V_{ja}$ and $V_{jb}$ represent the amplitudes of prediction vectors in $\alpha\beta$ plane, respectively. In addition, the selection of prediction vectors is in connection with the spatial position of RVV and the redundant vector pre-selection criterion in Section 3.1.

### 3.4 Improvement of the steady-state performance

For practice applications, dead-time is indispensable to prevent the short circuit of dc-link. Take phase A as an example, the ideal and actual PWM signals of switches along with the corresponding applied voltage are shown in Figure 10, where $t_d$ stands for the dead-time. It can be observed that the dead-time incurs a distorted voltage error $\Delta u_k$ ($k = a, b, c$) in phase voltage, which is in relation to not only $t_d$ but the current direction as well [25] and it can be expressed as:

$$\Delta u_k = \frac{t_d}{T_s} n_{dc} \cdot \text{sgn} (i_k)$$  \hspace{1cm} (23)

For other two phases, similar relations can be obtained, thereby the average three-phase voltage errors in VSC are governed by,

$$\begin{align*}
\Delta u_a &= |\Delta u_k| \cdot \left[ \frac{2\text{sgn} (i_a) - \text{sgn} (i_b) - \text{sgn} (i_c)}{3} \right] \\
\Delta u_b &= |\Delta u_k| \cdot \left[ \frac{2\text{sgn} (i_b) - \text{sgn} (i_a) - \text{sgn} (i_c)}{3} \right] \\
\Delta u_c &= |\Delta u_k| \cdot \left[ \frac{2\text{sgn} (i_c) - \text{sgn} (i_a) - \text{sgn} (i_b)}{3} \right]
\end{align*}$$  \hspace{1cm} (24)

In conventional MPC method, only one optimal voltage vector is selected and applied during each sampling period. This fact implies that the change of switching states only takes place at the beginning of each control period, with a dead-time deployed. However, it is noteworthy that the deployment of dead-time is not necessarily required for each sampling period, while it is imposed merely when the consecutive two switching states are different, namely switching state alters from 1 (or 0) to 0 (or 1). In addition from the VSC point of view, a certain switching pattern undoubtedly exists during the dead-time, and it also corresponds to a voltage vector, namely dead-time vector.

In order to further analyze the influence of dead-time vector on the control performance of MPC, the dead-time is supposed to exist in each sampling period, and the voltage vector $V_{25}$ is assumed to be the selected optimal voltage vector. Figure 11 shows the relationship among the RVV (located in Sector 3), the actual selected voltage vector, and different dead-time vectors $u_{dt}$ ($V_{05}, V_{15}, V_{35}, V_{45}, V_{55}, V_{65}, V_{75}$) in the case of $i_a > 0, i_b > 0, i_c < 0$. It can be easily found that the actual applied vector synthesized by the selected optimal one and the dead-time ones $V_{05}, V_{35}, V_{45}, V_{55}, V_{65}, V_{75}$ is nearer to the RVV than the selected optimal voltage vector, thereby leading to an enhanced steady-state performance. Rather, the employment of other dead-time vectors $V_{15}$ and $V_{65}$ will decrease the control performance. Table 4 exhaustively lists these two groups for different RVV sectors with optimal voltage vector $V_{25}$ in the case of $i_a > 0, i_b > 0, i_c < 0$.

![Diagram of the selected optimal voltage vector and different dead-time voltage vectors](image)

**FIGURE 11** Diagram of the selected optimal voltage vector and different dead-time voltage vectors

**TABLE 4** Dead-time vector classification for different RVV sectors with optimal voltage vector $V_{25}$ in the case of $i_a > 0, i_b > 0, i_c < 0$

| RVV sector | Beneficial dead-time vectors | Non-beneficial dead-time vectors |
|------------|------------------------------|--------------------------------|
| Sector 1   | $V_{05}, V_{35}, V_{55}, V_{75}$ | $V_{15}, V_{35}, V_{45}$ |
| Sector 2   | $V_{05}, V_{15}, V_{35}, V_{45}, V_{55}, V_{65}, V_{75}$ | $V_{35}, V_{45}$ |
| Sector 3   | $V_{05}, V_{35}, V_{45}, V_{55}, V_{75}$ | $V_{15}, V_{65}$ |
| Sector 4   | $V_{05}, V_{45}, V_{55}, V_{75}$ | $V_{15}, V_{35}, V_{65}$ |
so that, from this view, the duration of dead-time vector plays a key role in terms of steady-state performance. Intuitively, for a vector in unbeneficial group, the duration demands a value as small as possible. On the other hand, for a vector in beneficial group, the steady-state performance could be improved to a largest extent if a suitable duration is solved. The duration of the dead-time vector is therefore taken into account as a control variable. This variable is set as 2.5 $\mu$s to prevent a shoot-through problem, in the case of unbeneficial group; and in the event of beneficial group, it is solved by flux dead-beat control, as discussed in the following.

Assuming that the selected optimal voltage vector by cost function Equation (22) will be applied for $t_{\text{opt}}$ and the dead-time vector will stand for $T_s - t_{\text{opt}}$, based on the principle of DBFC, the vector durations and $q$-axis flux linkage slopes should follow:

$$
\psi_q(k+1) = \psi_q(k) + S_{\text{opt}} t_{\text{opt}} + S_{\text{dt}} (T_s - t_{\text{opt}}) = \psi_{\text{ref}}
$$

where $S_{\text{opt}}$ is the slope of the $q$-axis flux linkage with the selected optimal voltage vector; $S_{\text{dt}}$ is the slope of the $q$-axis flux linkage with the dead-time vector.

According to Equation (8), $S_{\text{opt}}$ and $S_{\text{dt}}$ can be primarily calculated as:

$$
S_{\text{opt}} = u_{q,\text{opt}} + R_i q + \omega_e (L_d i_d(k) + \psi_f)
$$

$$
S_{\text{dt}} = u_{q,\text{dt}} + R_i q + \omega_e (L_d i_d(k) + \psi_f)
$$

where $u_{q,\text{opt}}$ and $u_{q,\text{dt}}$ represent the $q$-axis components of the optimal voltage vector and the dead-time vector, respectively.

Obviously, by means of reasonably assigning the durations of the optimal voltage vector and the dead-time vector, the $q$-axis flux linkage will reach up to its reference $\psi_{\text{ref}}$ at the end of the sampling period. Then, by substituting Equations (26) and (27) into (25), the duration of the optimal voltage vector $t_{\text{opt}}$ can be solved as:

$$
t_{\text{opt}} = \frac{\psi_{\text{ref}} - \psi_q(k) - S_{\text{dt}} T_s}{S_{\text{opt}} - S_{\text{dt}}}
$$

A natural constraint is that if $t_{\text{opt}} < 0$ or $t_{\text{opt}} > T_s$, then $t_{\text{opt}} = 0$ or $t_{\text{opt}} = T_s$, respectively.

### 3.5 Summary of the proposed method

According to the abovementioned analysis, the control processes of the proposed method can be concluded as follow:

1. **Step 1**: Measure dc bus voltage, phase currents, machine position, and ZSC at $k$th.
2. **Step 2**: Judge the polarity of ZSC at $k$th, and obtain the redundant vector pre-selection criterion to suppress the ZSC in SOW-FSPMG system.
Step 3: Calculate the amplitude and position of RVV by DBFC method, and then determine the prediction vectors.

Step 4: Select the optimal voltage vector according to cost function in Equation (22).

Step 5: Determine the dead-time vector according to the phase current polarities and the selected optimal vector.

Step 6: Distinguish beneficial dead-time vectors and unbeneficial dead-time vectors, and calculate the duration of optimal vector and dead-time vector.
Step 7: Apply the corresponding voltage vectors on VSC.

4 | EXPERIMENTAL RESULTS

As presented in Figure 12, a 2 kW proof-of-concept prototype is established in order to verify the proposed method. The main parameters of the FSPMG are provided in Table 5. The VSC consists of three FF300R12ME4 modules that are produced by Infineon. LV25-P and HAS50-S from LEM are chosen to sample currents and dc-link voltage, respectively. The rotor position information is obtained by an E6B2-CWZ3E encoder from OMRON. Besides, the real-time control program is implemented using a DSPACE1104 digital control board, with a 10 kHz sampling frequency employed.

4.1 | ZSC suppression performance evaluation

At first, the proposed novel ZSC suppression strategy is evaluated in a manner where the speed is set as 400 rpm and the dc bus voltage reference is 90 V. The experiment conditions are determined by load box as well as experimental apparatus. The proposed ZSC suppression strategy is activated at \( t = 0.1 \) s, as presented in Figure 13(a). Meanwhile, the ZSC suppression performance of MPTC method in [16] is presented in Figure 13(b). It can be observed that when both ZSC suppression strategies are absent, the ZSC have obvious fluctuations; on the contrary, negligible ZSC are immediately resulted from activating the suppression strategy. As clearly demonstrated by the experimental results, excellent ZSC suppression performance can be achieved with both schemes. In addition to this, what should be mentioned is that the tedious tuning work of weighting factor is avoided in proposed method, as compared to conventional MPTC method in [16].

4.2 | Steady-state performance evaluation

Thereafter, the steady-state performance of the proposed method is tested. As foresaid, the improvement of steady-state performance is achieved by considering dead-time vector, for this respect, two methods are taken into account for comparison. For the sake of convenience, MPC-I refers to the RVV-based MPC method without considering the dead-time effect, whilst the proposed method is named MPC-II. In addition, the steady-state performance of conventional MPTC method in [16] is also conducted to make a
As seen, all three methods acquire sinusoidal currents, with stable torque and voltage obtained. Comparatively, the torque fluctuation for MPTC method in [16] is in a range of 4.2–6.6 Nm, while it ranges from 4.6 to 6.8 Nm and 5 to 6.4 Nm for MPC-I and MPC-II, respectively. Comparing MPC-I and MPC-II, it can be found that the torque ripple is highly reduced from 36.7% to 23.3%. In addition, the phase currents’ spectrums obtained using MATLAB are exhibited in Figures 14(d–f). As observed, the THDs of currents for three methods are 16.57%, 15.22% and 6.91%, respectively. The results demonstrate that the steady-state performance can be extremely improved by considering the dead-time effect, as discussed in Section 3.4. In fact, MPC-II can be deemed as a two-vector based MPC to some extent. This is so since that when the dead-time vector belongs to beneficial group, the selected vector and the dead-time vector are applied at the same time, in conjunction with their optimum duty-cycles solved by DBFC scheme.

Hereafter, the robustness of the proposed method against parameter variations is attested. Two cases, resistance increase and \( q \)-axis inductance increase, are carried out, as presented in Figure 15. The result corresponding to increasing stator resistance by a factor of 0.5 is seen in Figure 15(a). It confirms that the performance of the system is roughly unaffected by the resistance variation. On the other hand, as seen in Figure 15(b), when the \( q \)-axis inductance is increased by 50%, \( q \)-axis currents are of more ripples compared with Figure 15(a); however, the tracking error is still negligible, manifesting that the proposed method is robust in terms of inductance variation. To sum up, the proposed method performs a considerable robustness against parameter variations.

### 4.3 Dynamic performance evaluation

In this subsection, two experiments are implemented to investigate the dynamic performance for the proposed method. As shown in Figure 16, downing generated voltage operation is executed in a manner where the reference of dc bus voltage is abruptly changed from 100 to 80 V (under the speed of 400 rpm). As observed, the dc bus voltage can track its command quickly. The final value of \( i_d \) is about 1.9 A, accompanied with a constant \( d \)-axis current of 0 A. The ZSC can be well suppressed even during the dynamic process. In order to show dynamic performance more comprehensively, different voltage step change tests with higher speed are illustrated in Figure 17. It can be found that excellent dynamic performance can be achieved under different operation conditions.

In addition to the dc bus voltage step-change test, load step-change test is carried out as well, as shown in Figure 18. The load step-change is executed at 0.25 s, where the load is abruptly changed from 50 to 100 \( \Omega \) under the speed of 500 rpm. It is found that the dc bus voltage can be kept as a constant value of 110 V during the entire transient process, while the amplitude of \( q \)-axis current and phase current are regulated to follow the output power command. Meanwhile, the ZSC can be well suppressed during the whole process.
5 | CONCLUSION

In this work, an RVV-based MPC method considering dead-time vector is proposed and successfully conducted in a SOW-FSPMG system. The contributions of this work are concluded as following.

a. The redundant vector pre-selection criterion is firstly proposed to address the problem of ZSC in SOW-FSPMG system, avoiding the tedious tuning work of weighting factor in the cost function.

b. A DBFC method is adopted to obtain the RVV, by this manner, the prediction vectors can be readily determined and hence the computation burden reduction is achieved.

c. To further improve the steady-state performance of the whole system, the dead-time vector existed in FCS-MPC is analysed. A solution based on the insertion of the dead-time vector along with the selected optimal vector is developed.

All the merits of the proposed method are demonstrated-by-experiments.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study cannot be shared at this time as the data also forms part of an ongoing study.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Feng Yu provided project administration, guidance and supervision; Shuangshuang Zhao implemented the investigation, performed the experimental analysis and wrote the original draft; Xing Liu helped review and improve the paper; Wei Hua provided the resource. All authors have contributed significantly to this work.

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