Model Predictive Direct Power Control for Virtual-Flux-Based VSR With Optimal Switching Sequence

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Abstract
Three-phase voltage-source rectifier (VSR) has been widely used in energy, industry and other fields in the past few years. Model predictive control with optimal switching sequence (OSS-MPC) has further reduced output current THD and ripples with a constant switching frequency, compared with the conventional model predictive control (MPC). However, in practical application, the AC side voltage is often in a distorted state, which causes a distorted AC side current and a dramatic increase of THD. To overcome the drawback mentioned above, based on the analysis of OSS-MPC and combined with virtual flux oriented direct power control strategy, a virtual-flux-based model predictive direct power control strategy with optimal switching sequence (VF-OSS-MPDPC) is proposed in this paper. This control strategy for VSR combines the advantages of virtual-flux, low-pass filtering characteristics and optimal switching sequence model predictive control, which has high prediction accuracy and the AC current THD are greatly reduced under distorted AC voltage. The proposed control strategy can realize a constant switching frequency in steady-state operation without a modulator, which reduces the complexity of control strategy and the difficulty of AC side filter design. The proposed VF-OSS-MPDPC is validated through simulation and experiment compared with OSS-MPC, which proves the correctness and effectiveness of the proposed control strategy.

Index Terms
Virtual flux, VSR, optimal switching sequence, model predictive direct power control, voltage disturbance.

I. INTRODUCTION
Three-phase voltage-source rectifier (VSR) plays an important role in energy, industry and other fields because of its high power factor and controllable DC side voltage [1]. For example, converter station in HVDC transmission system, static var generator and mining converter [2].

After decades of research, a wide variety of power converter control methods have been developed. It can be roughly divided into two control modes. One is called linear control, which includes voltage oriented vector control (VOC) [3] and virtual-flux oriented control (VFOC) [4]. The other is called nonlinear control including model predictive control (MPC) [5] and direct power control (DPC) [6]. In the VOC control strategy, PI controllers are needed to adjust the stability of the system. Nevertheless, in practical application, the complexity of parameter adjustment of PI controller limit VOC’s development. The bandwidth of PI controller is usually much lower than MPC for a good gain margin [7]. Based on VOC and some improvements, [8] proposed VFOC. The basic principle is to regard the AC side voltage and filter as an AC motor. According to the mathematical model of VSR, the virtual-flux is estimated. Then, the amplitude and phase of the AC side voltage can be obtained through the virtual-flux. Because the integration in virtual-flux has low-pass filtering characteristics, VFOC not only has the advantage of eliminating voltage sensors, but also has a good inhibitory effect on AC voltage interference signals.
The main feature of MPC is that it can predict the control variables according to the mathematical model of the system. The optimal operation mode can be determined according to rolling optimization and cost function. It has the advantages of simple concept, fast dynamic response and flexible processing of multiple control objectives [9]. Based on the above advantages, MPC has been applied to the design of direct power control strategy (MPC-DPC). Meanwhile, MPC is divided into continuous control instructions model predictive control (CCS-MPC) and finite control set model predictive control (FCS-MPC) with discrete states according to whether the modulator is required. Compared with CCS-MPC, FCS-MPC requires less computation and no modulator. As a result, FCS-MPC makes full use of the discrete characteristics of VSR and applies an optimal switching state obtained by minimizing the cost function. However, some inherent defects hinder the wide application of FCS-MPC. For example, the lack of modulator will lead to obvious current ripple, variable switching frequency and diffused harmonic spectrum [10].

In order to overcome the problem that the switching frequency is not fixed and the harmonic spectrum is easy to diffuse, different MPC methods with fixed switching frequency are proposed in [11], [12]. [11] proposed deadbeat MPC strategy. This method is essentially continuous MPC, and a fixed switching frequency can be obtained through the modulator. A switching MPC method is proposed in [12], which uses FCS-MPC to quickly track the instantaneous reference value during transient and switch to modulation MPC mode when reaching steady state. However, the time of switching state is not easy to determine, which is easy to cause false triggering. In recent years, a multi vector MPC scheme has been proposed to generate a constant switching frequency instead of a single voltage vector in the traditional FCS-MPC scheme. A multi vector MPC with fixed switching frequency is proposed in [13]. Its working principle is that the vector switching sequence is executed once in each switching cycle, improving the steady-state performance. In order to further reduce the output current ripple, [14] introduced the concept of optimal switching sequence (OSS) in the multi vector MPC scheme. In essence, OSS provides the best way to select the voltage vector switching sequence to be applied. However, it still uses direct power control with voltage sensor to obtain instantaneous active and reactive power. According to the above analysis, the use of virtual-flux-based direct power control can reduce voltage sensors and improve the AC voltage interference of VSR. [4] proposed a current prediction method based on virtual-flux-based model predictive direct power control (VF-MPDPC) to predict direct power control under unbalanced power grid conditions. The influence of negative sequence component of AC voltage on virtual flux is compensated by band stop filter.

[15] proposed a model predictive control method with optimal switching sequence (OSS-MPC) to solve the problem that only one switching vector in each control cycle is selected in the traditional FCS-MPC, which leads to high output current ripples and variable switching frequency. However, voltage sensor is still adopted to measure AC side voltage in OSS-MPC, which increases equipment cost and the AC current THD and ripples under distorted AC voltage. In order to solve the above problems, a virtual-flux-based model predictive direct power control strategy with optimal switching sequence (VF-OSS-MPDPC) is proposed in this paper.

The rest of the paper is organized as follows. Section II introduces the concept of virtual flux. In Section III, the mathematic model of VSR is explained. The VF-OSS-MPDPC proposed in this paper is described in Section IV. Simulation implementation and experimental validation are shown in Section V. At last, the conclusion is provided in Section VI.

II. MODELING OF VSR VIRTUAL FLUX POWER CONTROL

Direct power control based on virtual flux orientation (VF-DPC) is developed from vector control based on grid voltage orientation. Its key is to regard the filter inductance $L$, filter resistance $R$ and AC voltage vector $E$ on the AC side of VSR as a virtual motor, where $L$ can be regarded as the stator leakage inductance of virtual motor and $R$ can be regarded as the stator resistance. Three phase VSR adopts half bridge circuit structure, as shown in Figure 1.

![Three phase VSR topology schematic diagram](image)

In Fig. 1, $n$ is the AC voltage neutral point, $e_a$, $e_b$ and $e_c$ are the AC side three-phase voltage, $i_a$, $i_b$ and $i_c$ are the rectifier phase current, $u_a$, $u_b$, $u_c$ are the rectifier output phase voltage, $C$ is the DC side energy storage capacitor, $U_{dc}$ is the DC voltage, and $R_L$ is the load resistance.

It is assumed that the characteristics of components in the circuit do not change with temperature, and the AC side is three-phase balanced voltage. The AC side voltages $e_a$, $e_b$, $e_c$ in the three-phase static abc coordinate are transformed into $\alpha\beta$ coordinate $e_\alpha$, $e_\beta$. According to the definition of virtual flux, it can be expressed as:

\[
\begin{align*}
\Psi_\alpha &= \int e_\alpha \, dt \\
\Psi_\beta &= \int e_\beta \, dt
\end{align*}
\]  

(1)

where $\Psi_\alpha$, $\Psi_\beta$ and $e_\alpha$, $e_\beta$ are the virtual flux and AC voltage under the $\alpha\beta$ coordinate system, respectively.

In VF-DPC control strategy, the instantaneous values of active power and reactive power can be estimated directly...
without voltage sensor. VF orientation principle is shown in Fig. 2.

In Fig. 2, $e_s$ is the AC side voltage; $i_s$ is AC side current; $u_s$ is the rectifier output phase voltage.

According to Kirchhoff’s voltage law and in combination with the VF orientation principle diagram shown in Fig. 2, it can be concluded that the AC side of VSR loop voltage equation in the $\alpha \beta$ coordinate system is:

$$
\begin{align*}
\dot{e}_\alpha &= L \frac{d}{dt} i_\alpha + R i_\alpha + u_{t\alpha} \\
\dot{e}_\beta &= L \frac{d}{dt} i_\beta + R i_\beta + u_{t\beta}
\end{align*}
$$

(2)

where $e_\alpha, e_\beta$ are the AC voltages, $\Psi_s$ is the virtual flux, $L$ and $R$ are the filter inductance and resistance respectively, $i_\alpha, i_\beta$ are the AC currents, $u_{t\alpha}, u_{t\beta}$ are the output phase voltages of VSR.

By introducing (2) into (1), it can be concluded that the relationship between virtual flux and AC side current and VSR output phase voltage is:

$$
\begin{align*}
\dot{\psi}_\alpha &= \int \left( L \frac{d}{dt} i_\alpha + R i_\alpha + u_{t\alpha} \right) dt \\
\dot{\psi}_\beta &= \int \left( L \frac{d}{dt} i_\beta + R i_\beta + u_{t\beta} \right) dt
\end{align*}
$$

(3)

According to (2), the derivative of $i_\alpha$ and $i_\beta$ with respect to time $t$ is:

$$
\begin{align*}
\frac{di_\alpha}{dt} &= \frac{1}{L} (e_\alpha - R i_\alpha - u_{t\alpha}) \\
\frac{di_\beta}{dt} &= \frac{1}{L} (e_\beta - R i_\beta - u_{t\beta})
\end{align*}
$$

(4)

In the $\alpha \beta$ coordinate, since the complex power vector can be represented by the ac voltage vector and the ac current conjugate vector, the instantaneous active power $p$ and reactive power $q$ can be represented by the virtual flux and current respectively:

$$
\begin{align*}
p &= \frac{d}{dt} \psi_c = i_\alpha \frac{d}{dt} \psi_c + i_\beta \frac{d}{dt} \psi_c + \omega \left( \psi_\alpha i_\beta - \psi_\beta i_\alpha \right) \\
q &= -\frac{d}{dt} \psi_c = i_\beta \frac{d}{dt} \psi_c + i_\alpha \frac{d}{dt} \psi_c + \omega \left( \psi_\alpha i_\beta + \psi_\beta i_\alpha \right)
\end{align*}
$$

(5)

where $\psi_c$ is the amplitude of the virtual flux vector.

This paper assumes the three-phase AC power supply is balanced, and the amplitude of virtual flux vector of grid voltage is constant, so the change rate of the corresponding flux amplitude is 0, i.e. $d\psi_c/dt = 0$. (5) can be reduced to:

$$
\begin{align*}
p &= \omega \left( \psi_\alpha i_\beta - \psi_\beta i_\alpha \right) \\
q &= \omega \left( \psi_\alpha i_\beta + \psi_\beta i_\alpha \right)
\end{align*}
$$

(6)

where $\omega$ is the fundamental frequency of AC voltage.

The derivative of both ends of (6) with respect to $t$ can obtain the rate of change of $p$ and $q$,

which is expressed by (7):

$$
\begin{align*}
\frac{dp}{dt} &= \omega \left( \frac{d}{dt} \psi_\alpha + \frac{d}{dt} \psi_\beta \right) - \omega \left( \psi_\beta u_{t\alpha} - \psi_\alpha u_{t\beta} \right) - \frac{R}{L} p - \omega q \\
\frac{dq}{dt} &= -\omega \left( \psi_\alpha u_{t\alpha} + \psi_\beta u_{t\beta} \right) - \frac{R}{L} q + \omega p
\end{align*}
$$

(7)

III. VSR MATHEMATICAL MODEL

As shown in the three-phase VSR circuit topology in Fig. 1, the two-level power circuit can realize the transmission of power from AC side to DC side. In order to avoid short-circuit faults caused by the pass-through of power diodes, each phase bridge arm has two different switching states: the upper bridge arm is on and the lower bridge arm is off or the upper bridge arm is off and the lower bridge arm is on. Therefore, there are $2^3 = 8$ switching states of three-phase VSR. The switching state $S_x (x = 1, \ldots, 6)$ of power conversion can be represented by three unipolar binary logic switching functions $S_a, S_b, S_c$, i.e. [16].

$$
S_a = \begin{cases} 
1, \quad S_{1\text{ON}}, S_{1\text{OFF}} \\
0, \quad S_{1\text{OFF}}, S_{2\text{ON}}
\end{cases}
$$

(10)

$$
S_b = \begin{cases} 
1, \quad S_{2\text{ON}}, S_{2\text{OFF}} \\
0, \quad S_{2\text{OFF}}, S_{3\text{ON}}
\end{cases}
$$

(11)

$$
S_c = \begin{cases} 
1, \quad S_{3\text{ON}}, S_{3\text{OFF}} \\
0, \quad S_{3\text{OFF}}, S_{6\text{ON}}
\end{cases}
$$

(12)

According to the VSR circuit structure, the rectifier output voltage can be represented by the above switching signal and
DC voltage, as shown below.

\[
\begin{align*}
    u_x &= \frac{2U_{dc}}{3} \left[ S_a - \frac{1}{2} (S_b + S_c) \right] \\
    u_y &= \frac{2U_{dc}}{3} \left[ S_b - \frac{1}{2} (S_a + S_c) \right] \\
    u_z &= \frac{2U_{dc}}{3} \left[ S_c - \frac{1}{2} (S_a + S_b) \right]
\end{align*}
\]

(13)

Where \( U_{dc} \) is the DC voltage, \( u_x, u_y \) and \( u_z \) are the output voltage of phase a, b and c of the rectifier.

Since the solution of virtual flux is in \( \alpha \beta \) coordinate system, it is necessary to transform the three-phase abc coordinate system into \( \alpha \beta \) coordinate system by Clarke transformation. Therefore, the rectifier output voltage vector \( \mathbf{u}_c \) can be expressed as:

\[
\mathbf{u}_c = u_{r\alpha} + ju_{r\beta} = T_{clark} \left[ u_x \quad u_y \quad u_z \right]^T
\]

(14)

\( T_{clark} \) is as follows:

\[
T_{clark} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & \sqrt{3} \end{bmatrix}
\]

(15)

Substitute (13) into (14) to obtain (16)

\[
\begin{align*}
    u_{r\alpha} &= \frac{2U_{dc}}{3} \left[ S_a - \frac{1}{2} (S_b + S_c) \right] \\
    u_{r\beta} &= \frac{U_{dc}}{\sqrt{3}} (S_b - S_c)
\end{align*}
\]

(16)

According to the theory of space vector modulation, VSR can be approximated as a linear system, but in this paper, VSR is regarded as a nonlinear discrete system with only eight different voltage vectors output, among which two voltage vectors are 0. The eight voltage vectors of VSR output are defined as \( u_{r\alpha,x} = u_{r\alpha} + ju_{r\beta,x} (x = 0, 1, \ldots, 7) \). The relationship between the switching state of VSR and the output voltage vector is shown in Table 1.

Table 1: Switching states and voltage vectors of a VSR.

| Index | Switching state \( S_j \) | \( u_{r\alpha} \) | \( u_{r\beta} \) |
|-------|-----------------------------|----------------|----------------|
| 0     | \( S_{0\alpha} \)           | 0              | 0              |
| 1     | \( S_{1\alpha} \)           | 1              | 0              |
| 2     | \( S_{2\alpha} \)           | 1              | \( U_{dc}/3 \) |
| 3     | \( S_{3\alpha} \)           | 0              | \( -U_{dc}/3 \) |
| 4     | \( S_{4\alpha} \)           | 0              | \( -2U_{dc}/3 \) |
| 5     | \( S_{5\alpha} \)           | 0              | \( -\sqrt{3}/3 \) |
| 6     | \( S_{6\alpha} \)           | 1              | \( -U_{dc}/3 \) |
| 7     | \( S_{7\alpha} \)           | 1              | 0              |

Obviously, 8 different switching states \( S_x \) correspond to 8 different spatial voltage vectors \( \mathbf{u}_{r\alpha,x} \), respectively. Except for the two zero vectors, the other 6 non-zero voltages are uniformly distributed in the \( \alpha \beta \) coordinate system. Any given space voltage vector can be represented by the composition of other voltage vectors near its sector. In [19], the \( \alpha \beta \) coordinate system is divided into 12 sectors, and each sector is composed of the corresponding 6 known voltage vector sequences. According to the sector where the AC voltage is located, the optimal voltage vector sequence acting on the rectifier during the sampling interval \( T_s \) is selected. Although this method can restrain the ripple of output current, it requires a lot of calculation. [15] proposed an improved voltage vector switching sequence allocation method. The \( \alpha \beta \) coordinate system is divided into six sectors, and each sector is described by a voltage vector sequence composed of eight corresponding known voltage vectors. The relationship between sector division and the eight known VSR output voltage vectors is shown in Fig. 3.

![FIGURE 3. VSR output voltage vector and partition.](image)

Compared with FCS-MPC, OSS-MPC, as a multi vector MPC strategy, pays more attention to the voltage change trajectory between two adjacent sampling times based on the predicted trajectory.

The optimal switching sequence of voltage vector can be determined from Fig. 3. The sequence of voltage vectors assigned to each sector is defined as \( u_{rj} = \{u_1, u_2, u_3, u_4, u_5, u_6, u_7, u_8\} \) (\( j = 1, 2, \ldots, 6 \), indicates the sector number). The first four voltage vectors are arranged symmetrically with the last four. In Fig. 3, \( u_1 \) is the voltage vector output by VSR. When \( u_{rj} \) falls in sector 1, \( u_1 \) can be represented by \( u_{1} = \{u_{r0}, u_{r1}, u_{r2}, u_{r7}, u_{r6}, u_{r5}, u_{r4}\} \) voltage switching sequence. The voltage vector switching sequence corresponding to different sectors is shown in Table 2.

Therefore, according to the voltage vector switching sequence \( u_{rj} \) in Table 2, the corresponding relationship between the VSR output voltage vector and the sector can be accurately determined. The eight output voltage vectors in \( u_{rj} \) are composed of four zero vectors and two pairs of the same non-zero vectors. The two complex voltage vectors in the \( \alpha \beta \) coordinate are represented by the voltage vector \( \mathbf{u}_{r\alpha,x} \) in Table 1. At the same time, the switching states \( S_j \) can also be judged to prepare for the calculation of the optimal output duty cycle later.

IV. MODEL PREDICTIVE CONTROL FOR OPTIMAL SWITCHING SEQUENCE

After selecting the voltage switching sequence, the duration \( t_{rj1}, t_{rj2} \) of the three different voltage vectors \( \mathbf{u}_{r\alpha,x} \) in the switching sequence should be determined respectively [17]. According to the instantaneous change rate of instantaneous
TABLE 2. Sector and vector switching sequence.

| Sector | Voltage vector switching sequence $u_{ij}$ |
|--------|------------------------------------------|
| 1      | $\{u_{00}, u_{12}, u_{21}, u_{37}, u_{58}, u_{64}, u_{16}, u_{10}\}$ |
| 2      | $\{u_{03}, u_{25}, u_{52}, u_{27}, u_{57}, u_{28}, u_{65}, u_{16}\}$ |
| 3      | $\{u_{06}, u_{33}, u_{33}, u_{55}, u_{65}, u_{16}, u_{10}\}$ |
| 4      | $\{u_{03}, u_{25}, u_{52}, u_{27}, u_{57}, u_{28}, u_{65}, u_{16}\}$ |
| 5      | $\{u_{06}, u_{33}, u_{33}, u_{55}, u_{65}, u_{16}, u_{10}\}$ |
| 6      | $\{u_{00}, u_{12}, u_{21}, u_{37}, u_{58}, u_{64}, u_{16}, u_{10}\}$ |

active power $p$ and reactive power $q$ during the action of voltage vector expressed in (9), they can be defined as:

$$f_{pi} = \frac{dp}{dt} \quad f_{qi} = \frac{dq}{dt}$$

where subscript ‘$i$’ represents the position sequence number ($i = 1, \ldots, 8$) of the applied voltage in the voltage vector sequence. For example, the third voltage vector in the voltage sequence $u_2$, i.e. $j = 2$, $i = 3$, represents the voltage vector $u_{62}$.

In this way, the change trajectories of $p$ and $q$ in the relevant action time under the action of a given VSR voltage vector can be calculated, and the mathematical expression is as follows:

$$p_i = p_{i-1} + f_{pi}t_{ij} \quad q_i = q_{i-1} + f_{qi}t_{ij}$$

where $[p_{i-1}, q_{i-1}]$ represents the initial values of power while the $i$-th voltage vector starts to act in the voltage switching sequence. $t_{ij}$ represents the time of voltage vector action, and $t_{ij} = t_{ij} = t_{i2j} = t_{i2j} = t_{i1j}, t_{i1j} = t_{i1j}, t_{i2j} = t_{i2j}$, $t_{i2j} = t_{i2j} = t_{i0j}$. $t_{i1j}$ stands for zero voltage vector action time; $t_{i1j}$ represents the action time of the first effective voltage vector; $t_{i2j}$ represents the action time of the second effective vector. $\{p_i, q_i\}$ represents the active and reactive power when the voltage vector ends. Fig. 4 illustrates the change trend of $p$ and $q$ from time $k$ to $k + 1$.

Where power change rate $f_{p1} = f_{p4} = f_{p5} = f_{p6} = f_{p7}$, $f_{p3}$, $f_{p2}$ = $f_{p6}$; $f_q$ similarly. $p_0$ and $q_0$ are instantaneous power values at the current sampling time.

After traversing and solving the voltage vector switching sequence corresponding to the six different sectors, a set of voltage sequences that can minimize the cost function value is found, which can be regarded as the optimal switching sequence. Then, the optimal switching state required by power devices can be solved by using the optimal switching sequence. The emphasis of this idea lies in the establishment of cost function and the solution of voltage vector action time $t_{0ij}$, $t_{s1j}$ and $t_{s2j}$.

In OSS-MPC, the optimal operation mode is determined by minimizing the cost function. Therefore, the cost function of VF-OSS-MPDC proposed in this paper is expressed as

$$G(t_{0j}, t_{s1j}, t_{s2j}) = \sum_{i=1}^{8} (p_{ref} - p_i)^2 + (q_{ref} - q_i)^2$$

where $p_{ref}$ and $q_{ref}$ are the reference active power and the reference reactive power respectively. $p_{ref}$ is obtained by the outer loop of power and voltage. Since VSR operates at a unit power factor, $q_{ref}$ is set to 0.

Using the condition of minimum-solution of cost function:

$$\begin{cases} \frac{\partial G(t_{0j}, t_{s1j}, t_{s2j})}{\partial t_{s1j}} = 0 \\ \frac{\partial G(t_{0j}, t_{s1j}, t_{s2j})}{\partial t_{s2j}} = 0 \end{cases}$$

By solving (20), $t_{0j}$, $t_{s1j}$ and $t_{s2j}$ that minimize the cost function are as follows:

$$t_{s1j} = \frac{(f_{q2} - f_{q3})e_{pk} + (f_{p3} - f_{p2})e_{qk} + (f_{p2}f_{q3} - f_{p3}f_{q2})T_s}{2((f_{q2} - f_{q3})f_{p1} + (f_{p3} - f_{p2})f_{q2} + (f_{p1} - f_{p2})f_{p3})}$$

$$t_{s2j} = \frac{(f_{q3} - f_{q4})e_{pk} + (f_{p4} - f_{p3})e_{qk} + (f_{p4}f_{q3} - f_{p3}f_{q4})T_s}{2((f_{q3} - f_{q4})f_{p1} + (f_{p4} - f_{p3})f_{q2} + (f_{p4} - f_{p3})f_{p3})}$$

$$t_{0j} = (T_s/2 - t_{s1j} - t_{s2j})/2$$

where $e_{pk} = p_{ref} - p_k$, $e_{qk} = q_{ref} - q_k$, $p_k$ and $q_k$ can be derived from (6).

The difference from the definition of cost function used in traditional FCS-MPDC is that the cost function used in this paper evaluates the predicted values of instantaneous active power and reactive power at 8 different times in the sampling period. The traditional FCS-MPDC cost function only evaluates the difference between the instantaneous power prediction value and the power reference at the next time, and so accuracy of the model is not high. The comparison of the two cost functions is shown in Figure 5.

$p_0$ in Fig 5 is equal to the instantaneous active power $p_k$. Obviously, the traditional VF-FCS-MPDC only focuses on minimizing the active power tracking error within each sampling interval $T_s$. However, VF-OSS-MPDC is based on the predictive trajectories, which aim to globally minimize power prediction errors within one $T_s$, (the predicted difference of power $p$ is shown in the red part in Fig. 5). Therefore, the power gradient is adjusted under multiple degrees of freedom.
to comprehensively measure the minimum value of the cost function, which enables the prediction result more accurate.

In the cost function \( G(t_{s0j}, t_{s1j}, t_{s2j}) \), the instantaneous power change rates \( f_{pi} \) and \( f_{qi} \) used to predict \( p_i \) and \( q_i \) are obtained by using the virtual flux, which saves the AC voltage sensor compared with the traditional DPC using voltage sensor. Due to the voltage integration characteristics of the virtual flux, it is equivalent to a low-pass filter, which can effectively eliminate the influence of voltage harmonics and current ripple. Therefore, the accuracy of VF orientation is higher than that of VOC orientation. In addition, the cross compensated virtual flux observer [18] used in this paper can compensate the phase angle difference between the actual flux vector and the virtual flux vector.

In this paper, the first-order low-pass filter is used as the filtering link of DC bias. The estimated value of virtual flux on the grid side can be expressed as follows

\[
\psi^* = \frac{e^{j\omega t}}{\omega + \omega_c} \tag{22}
\]

where \( \psi^* \) represents the estimated value of the virtual flux vector.

The polar coordinate representation of the flux is:

\[
\begin{align*}
\psi &= \psi \angle \theta \\
\psi^* &= \psi^* \angle \theta^*
\end{align*} \tag{23}
\]

From equation (23), equation (24) can be obtained:

\[
\frac{\psi^*}{\psi} = \frac{e^{j\omega t}}{\sqrt{\omega^2 + \omega_c^2}} \angle \phi \tag{24}
\]

where \( \psi \) and \( \psi^* \) represent the actual virtual flux and the estimated virtual flux, respectively. \( \theta \) and \( \theta^* \) represent the phase of the corresponding flux, and \( \phi = \arctan(\omega_c + \omega) \).

The vector relationship between the two virtual flux vectors is shown in Figure 6.

According to (25) and (26), the principle of cross compensated virtual flux observer can be obtained, as shown in Fig. 7.

According to (25) and (26), the principle of cross compensated virtual flux observer can be obtained, as shown in Fig. 7.

In Fig. 6, \( \omega_c \) is the cutoff frequency of the first-order low-pass filter; \( \omega \) is fundamental angular frequency; \( \psi^* \) is the estimated virtual flux vector; \( \psi \) is the actual virtual flux vector.

The correct selection of optimal switch sequence is very important for the proposed VF-OSS-MPDPC control strategy. The selection procedure is as follows:

1) In each control cycle, firstly, the instantaneous change rates \( f_{pi} \) of the corresponding active power \( p \) and the instantaneous change rates \( f_{qi} \) of the corresponding reactive power \( q \) are calculated from the six voltage vector sequences corresponding to the six sectors.

2) Then, the instantaneous power values \( p_i \) and \( q_i \) corresponding to the \( i \)th voltage vector in the voltage vector sequence are predicted by using the instantaneous change rate \( f_{pi} \) and \( f_{qi} \).
3) Next, six different voltage vector sequences are optimized by using the cost function. The voltage vector sequence corresponding to the instantaneous power with the minimum cost function value is considered as the optimal switching sequence (OSS), defined as \( u_{op} = u_{aop} \). The sector \( j \) corresponding to this group of OSS is considered to be the optimal sector. At the same time, the action time of zero vector and two non-zero vectors corresponding to \( u_{aop} \) are \( t_{s0j} \), \( t_{s1j} \) and \( t_{s2j} \) respectively. The optimal voltage vector action time is expressed as \( T_{op} = \{ t_{s0op}, t_{s1op}, t_{s2op} \} \).

4) Last, the output optimal duty cycle \( d_{op} \) is calculated using OSS and \( T_{op} \).

In order to realize the proposed VF-OSS-MPDPC in view of the digital implementation, it is necessary to convert the optimal voltage vector action time \( T_{op} \) into optimal duty cycle \( d_{op} \). The calculation formula is as (27), shown at the bottom of the page, where \( u_{aop}(0) \), \( u_{aop}(1) \) and \( u_{aop}(2) \) are the zero voltage vector, the first effective vector and the second effective vector in the optimal voltage vector switching sequence \( u_{aop} \), respectively. \( S_{x} \) is the switching state of abc three-phase corresponding to voltage vector \( u_{x} \). Table 1. Example, when the OSS is selected as \( u_{a2} \), that is, \( j = 2 \), and the VSR output voltage falls in sector 2, the corresponding relationship of \( d_{op} \) is shown in Fig. 8.

Aiming at the problems of large output current ripple and variable switching frequency of VSR, the proposed VF-OSS-MPDPC control strategy in this paper can calculate the switching time of the optimal voltage vector switching sequence through the instantaneous power change rate represented by the virtual flux. This method eliminates the AC voltage sensor and improves the robustness of AC side voltage. The principle of VF-OSS-MPDPC is shown in Fig. 9.

V. SIMULATION AND EXPERIMENTAL VERIFICATION

A. SIMULATION ANALYSIS

Reference [19] proposed direct power model predictive control based on the optimal switching sequence (OSS-MPDPC), which calculates the instantaneous active and reactive power by collecting the three-phase voltage and three-phase current at the AC side. Then the gradients of instantaneous active power and instantaneous reactive power are calculated according to (28). Meanwhile, the optimal switching state is obtained by the model predictive control of the optimal switching sequence.

\[
\begin{align*}
\frac{dp}{dt} &= v_a \left( \frac{1}{L} (u_{a} - v_a) + \omega \beta \right) \\
&+ v_b \left( \frac{1}{L} (v_{b} - u_{b}) - \omega \alpha \right) \\
\frac{dp}{dt} &= v_b \left( \frac{1}{L} (u_{b} - v_{b}) + \omega i_b \right) \\
&- v_a \left( \frac{1}{L} (v_{b} - u_{a}) - \omega i_a \right)
\end{align*}
\]  

(28)

In order to verify the effectiveness of the algorithm proposed in this paper, a VSR simulation model is built in Matlab/Simulink environment, compared with OSS-MPDPC algorithm [19]. Table 3 shows the simulation parameters.

Fig. 10 (a) shows the output phase voltage of VF-OSS-MPDPC, Fig. 10 (b) shows the AC side current and Fig. 10 (c) shows the harmonic spectrum of the AC side current. It can be seen from Fig. 10 that VF-OSS-MPDPC can output standard three-phase sinusoidal current with low ripple and THD.

Fig. 11(a) shows the output phase voltage of OSS-MPDPC, Fig. 11(b) shows the network side current and Fig. 11(c) shows the harmonic spectrum of the network side current.

By comparing Fig. 10 and Fig. 11, the THD of grid-side current under the application of the two algorithms is similar, but OSS-MPDPC requires a voltage sensor to collect the grid
voltage in real time. In practical application, the voltage sensor may bring noise and interference, making the reliability of the whole system be affected because of the possible error value. In contrast, VF-OSS-MPDPC uses virtual flux and eliminates the need for AC side voltage sensors, reducing the system size and costs, being more robust of AC voltage.

However, in the actual power grid, there are always various harmonics in the three-phase voltage source, which distorts the current on the AC side and increases the current ripple and THD on the AC side. Because virtual flux has the function of voltage integration, which is equivalent to a low pass filter, it can effectively filter the harmonic components in the voltage source and greatly reduce the current output ripple and THD of the network side.

In order to verify the performance of VF-OSS-MPDPC in the case of AC side distortion, the VF-OSS-MPDPC algorithm and the OSS-MPDPC algorithm [19] were simulated and compared in the case of three-phase AC voltage distortion.

Fig. 12 shows the output waveform of VF-OSS-MPDPC under the condition of three-phase voltage distortion (10% positive sequence 5th harmonic is injected into the three-phase voltage source). In this state, the three-phase AC voltage is still in equilibrium, so equation (5) is still valid. Fig. 12 (a) shows the voltage waveform when the three-phase voltage is distorted. Due to the low-pass filtering characteristics of virtual flux, the three-phase current on the AC side can still be maintained as the three-phase sinusoidal current. At the same time, the current ripple can be greatly reduced and the THD value is relatively low, as shown in Fig. 12 (b) and (c) respectively.

However, for OSS-MPDPC, the voltage sensor is used to directly sample the distorted voltage, resulting in large
distortion of the current at the AC side and a dramatic increase of the current ripple and THD at the AC side, which cannot meet the power quality requirements, as shown in Fig. 13 (a) and (b).

Fig. 14(a)-(c) shows the dynamic performance under the proposed control mode. At 1.8 seconds the load changes from 80Ω to 50Ω. Fig. 14(a) shows that when the load changes suddenly, the three-phase current at the AC side can quickly follow the load changes. Fig. 14(b) shows that active power and reactive power can also respond quickly to load mutation. In Fig. 14(c), the DC side voltage will produce a slight drop after the load mutation, but it will quickly recover to the steady-state set value.

Figure 15. (a) shows the change of grid side current when reactive power steps, and Figure 15. (b) shows the change of power. At 1.8 seconds, the given value of reactive power of the system changes from 0 to 500Var. It can be seen that when the reactive power steps, the network side current will quickly
stabilize and the reactive power will quickly follow the given value.

B. EXPERIMENTAL VERIFICATION

In order to verify the effectiveness of the proposed algorithm, VF-OSS-MPDC was validated experimentally. The main circuit switching device of the experiment is IGBT BSM50GB120DLC, the controller uses TMS320F28335 of TI Company, and the voltage and current sampling modules are LV25-P and LA25-NP sensors respectively, as shown in Fig. 16. Experimental parameters are shown in Table 4.

Fig. 17 and Fig. 18 show waveform and power quality analysis of the AC side current of VF-OSS-MPDC and OSS-MPDC under ideal voltage source.

Where $U_{dc}$ is the DC side voltage, $i_a$ is the grid side current, and $e_a$ is the grid voltage. By comparing the two figures, it can be seen that under ideal voltage source, VF-OSS-MPDC and OSS-MPDC can output normal three-phase sinusoidal current, keep low network side current THD and ripple, and stabilize DC side voltage to a given value. The AC side current THD of VF-OSS-MPDC is relatively poor, but also within the acceptable range.
Fig. 19 and Fig. 20 show waveform and power quality analysis of AC side current of VF-OSS-MPDPC and OSS-MPDPC in the case of distorted voltage source. It can be seen that in the case of distorted grid, the traditional OSS-MPDPC has a large AC side current distortion, and its THD reaches 10.5%. However, for VF-OSS-MPDPC, due to the integration of virtual flux, the net side current distortion is greatly reduced, and its THD is 5.9%, which is far less than the traditional OSS-MPDPC algorithm.

Fig. 21 shows the waveform of DC side voltage $U_{dc}$ rising from 130V to 140V. It can be seen from the figure that when the reference DC voltage changes suddenly, the current on the AC side can respond quickly, and the DC voltage can also reach the given value quickly.

Fig. 22 shows the waveform of DC side voltage $U_{dc}$ drops from 140V to 130V with VF-OSS-MPDPC.

It is worth noting that the calculation error of virtual flux is caused by the problem of integral drift in integration [18]. Therefore, the cross-compensation virtual flux observer was adopted in the observation of virtual flux in this paper, which can observe virtual flux more accurately. However, its parameter $\omega_c$, namely the cut-off frequency of first-order low-pass filter, will greatly affect the observation of virtual flux. The $\omega_c$ of the above experiments is 0.5. According to [18], the larger $\omega_c$ is, the faster the virtual flux reaches steady state, and the smaller the error of virtual flux observation is. Fig. 23 shows the experimental results when the cut-off frequency $\omega_c$ is 0.1.
It can be seen from the figure that when the \( \omega_c \) is reduced to 0.1, the current ripple and THD on the AC side increase greatly, that is, the observation error of virtual flux increases. Therefore, in general cases, the higher the cut-off frequency \( \omega_c \) is, the faster the virtual flux reaches the steady state, the smaller the error of the virtual flux observation, and the smaller the current ripple and THD at the AC side.

VI. CONCLUSION

The traditional model predictive direct power control strategy with optimal switching sequence based on voltage sensor (OSS-MPDPC) has the disadvantages of poor anti AC side voltage disturbance performance in the case of AC side voltage distortion. Therefore, this paper proposes a model predictive direct power control method with optimal switching sequence based on virtual flux (VF-OSS-MPDPC). Based on the traditional model predictive direct power control (OSS-MPDPC) of optimal switching sequence, this method combines virtual flux to eliminate the voltage sensor and reduce the system volume and cost. At the same time, due to the integration effect of virtual flux, the current ripple and THD on the grid side can be effectively reduced under the condition of distorted grid. At the same time, it can better resist voltage interference. Simulation and experimental results verify the feasibility of the proposed algorithm.

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