An Improved FCS-MPC Based on Virtual Vector Expansion and Sector Optimization for 2L-VSCs

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ABSTRACT Conventional finite control set model predictive control (FCS-MPC) outputs one voltage vector per period by vector traversal algorithm, which leads to low control accuracy, unnecessary high computational burden and unfixed switching frequency. In this paper, an improved FCS-MPC based on virtual vector expansion and sector optimization is proposed to improve system performance and reduce computational burden for 2L-VSCs. Three aspects are improved as follows. First, a sector optimization method based on effective vector radiation range is proposed to directly determine the optimal vector without vector traversal. Second, a virtual vector expansion method based on vector synthesis algorithm with fixed 1/4 & 1/2 & 3/4 duty cycle is proposed to expand optional vectors from 8 to 44, and improve vector accuracy and system performance. Third, a modulated vector output mode is adopted per period to fix switching frequency and decrease current harmonics. Finally, the advantages of proposed MPC are verified by simulation and experiment.

INDEX TERMS 2L-VSCs, FCS-MPC, sector optimization, virtual vector expansion, modulated vector output.

I. INTRODUCTION Three-phase two-level voltage source converters (3P-2L-VSCs) have been widely used in renewable energy power generation system, motor drive system and electric vehicle charging system due to their simple structure and convenient control [1], [2]. Therefore, 3P-2L-VSC system shown in Fig. 1 is adopted in this paper.

Conventional proportional integral control for 3P-2L-VSCs suffers from cumbersome parameters adjustment, and these parameters are only applicable to a specific working condition, which is difficult to balance system steady-state and transient performance [3], [4]. With the rapid development of microprocessors, finite control set model predictive control (FCS-MPC) has been concerned and applied in converter control field increasingly, due to its advantages of simultaneous processing for multiple targets and constraints, fast dynamic response and easy implementation [5], [6]. Conventional FCS-MPC utilizes discrete characteristics of converters switching states [7]. It predicts system states under all switching states through predictive equation, then evaluates system performance through cost function containing control targets and constraints, and finally determines the optimal switching state as control output [8], [9].

However, there are some challenges in application of conventional FCS-MPC [10], [26]. First, vector traversal algorithm is adopted to determine the optimal vector from all converter switching states, which leads to high and unnecessary computational burden for microprocessor [11], [12]. Second, only one switching state is determined in one cycle, which leads to unfixed switching frequency and low control accuracy with relatively large output current ripple [13], [14].

In order to reduce computational burden, some improved algorithms are mentioned in [15], [16], and [17]. In [15], a low-complexity MPC algorithm is proposed for 3P-2L AC/DC converters to reduce computational burden, and the negative conjugate of complex power in synchronous frame is selected for power predictive control. In [16] and [17], a simplified FCS-MPC is proposed based on equivalent transformation and sector distribution methods, which decreases
the number of voltage vectors involved in vector traversal algorithm, and reduces computational burden without affecting control performance. However, the mentioned methods could not determine the optimal vector directly.

In order to improve vector control accuracy, some improved algorithms are mentioned in [18], [19], [20], [21], [22], [23], and [24] by increasing the number of applied vectors in one cycle. In [18], [19], and [20], some algorithms based on double vectors are proposed to improve vector control accuracy. In [18], the applied combined vectors per period are only zero and non-zero vectors, and such inadequate vector combinations could improve control accuracy slightly. In contrast, in [19] and [20], two non-zero vectors could be applied in one cycle as well, and vector accuracy is further improved compared with [18]. However, the system tracking error would be significantly reduced only if optional vectors are adequate.

Besides, some algorithms based on multiple vectors are proposed to track reference vector [22], [23], [24]. In [22], a new insight of multi-vector algorithm determines the optimal vector and corresponding duty cycle without vector enumeration and repetitive state prediction. In [23] and [24], vector control accuracy is improved by multiple vectors, whose vector operation times are determined by cost function and trigonometric function respectively. In [25], a multi-vector algorithm increases optional vectors to 20 according to space vector modulation, and optimizes vector selecting process according to dead-beat control. However, inevitable vector enumeration would increase computational complexity in mentioned literatures.

In this paper, in order to solve the flaws of conventional FCS-MPC, an improved FCS-MPC based on virtual vector expansion and sector optimization is proposed. First, a sector optimization method based on effective vector radiation range is proposed to directly determine the optimal vector without vector traversal. Second, a virtual vector expansion method based on vector synthesis algorithm with fixed 1/4 &1/2 & 3/4 duty cycle is proposed to improve vector control accuracy, which expands optional vectors from 8 to 44 and has the same control effect similarly with multiple vectors synthesis. Third, the modulated vector output mode is adopted to fix switching frequency and decrease current harmonics. Finally, the proposed MPC are verified by simulation and experiment.

II. SYSTEM MODELING AND CONVENTIONAL FCS-MPC
A. SYSTEM MATHEMATICAL MODELING
In Fig. 1, the equations of 3P-2L-VSC system in dq coordinate system are expressed as:

\[
\begin{align*}
\dot{u}_q &= -R_s i_q - L_s \frac{di_q}{dt} + e_q + \omega L_s i_d \\
\dot{u}_d &= -R_s i_d - L_s \frac{di_d}{dt} + e_d + \omega L_s i_q \\
C \frac{du_{dc}}{dt} + \frac{u_{dc}}{R_L} &= \frac{3}{2} \frac{e_d i_d + e_q i_q}{u_{dc}}
\end{align*}
\]

where \(u_{dc}\) and \(e_{d,q}\) are d-axis and q-axis voltage components of converter and grid; \(i_{d,q}\) are active and reactive currents; \(\omega\) is rotational angular velocity of grid voltage; \(L_s\) and \(R_s\) are AC-side inductance and its internal resistance; \(C\) and \(R_L\) are DC-side capacitor and resistance load; \(u_{dc}\) is DC voltage.

B. CONVENTIONAL FCS-MPC STRATEGY

Conventional FCS-MPC consists of prediction equation, cost function and voltage vector traversal optimization.

First, system prediction equation is obtained by discretizing system equation (1), and expressed as:

\[
\begin{align*}
i_{d,q}^{k+1} &= i_{d,q}(k) + T_s (e_{d,q}(k)) \\
\end{align*}
\]

where \(i_{d,q}^{k}\) are predictive currents; \(u_{d,q}(k)\) are d-axis and q-axis components of voltage vector; \(T_s\) is sampling period.

Second, cost function (g) is constructed by absolute error between predictive and reference currents, and expressed as:

\[
g = \left| i_{d,q}^{k+1} - i_{d,q}^* \right| + \left| i_{d,q}^{k} - i_{d,q}^* \right|
\]

Third, vector traversal algorithm is adopted to seek the optimal one from 8 basic voltage vectors, which is determined by the minimum \(g\), and expressed as:

\[
V_{\text{opt}}(k) = V_{\arg \min \{g(i(V_m))\}, m \in [1,2,8]}
\]

where \(V_{\text{opt}}(k)\) is the optimal voltage vector; \(\arg \min \{g(i(V_m))\}\) is voltage vector subscript function corresponding to the minimum \(g\).

Besides, voltage vector that is determined by converter switching states in dq coordinate system is expressed as (6), and listed in TABLE 1.

\[
V = \frac{2}{3} u_{dc} (s_a + s_b e^{j2\pi} + s_c e^{-j2\pi}) e^{-j\theta}
\]

where \(s_a, s_b\) and \(s_c\) are switching states of phase a, phase b and phase c respectively; \(\theta\) is rotational angle of grid voltage vector.

Locations of 8 basic vectors and 6 conventional sectors that take basic vectors as sector boundary are shown in Fig. 2.
TABLE 1. Switching states and 8 basic voltage vectors.

| s_x | s_y | s_z | Basic voltage vectors |
|-----|-----|-----|-----------------------|
| 0   | 0   | 0   | V_1 = 0               |
| 0   | 0   | 1   | V_2 = (-1/3+j\sqrt{3}/3)V_{dc}e^{j\theta} |
| 0   | 1   | 0   | V_3 = (-1/3+j\sqrt{3}/3)V_{dc}e^{j\theta} |
| 0   | 1   | 1   | V_4 = (-2/3)V_{dc}e^{j\theta} |
| 1   | 0   | 0   | V_5 = 2/3V_{dc}e^{j\theta} |
| 1   | 1   | 0   | V_6 = (1/3+j\sqrt{3}/3)V_{dc}e^{j\theta} |
| 1   | 1   | 1   | V_7 = (1/3+j\sqrt{3}/3)V_{dc}e^{j\theta} |

FIGURE 2. Basic vectors and conventional sectors.

C. FLAWS OF CONVENTIONAL FCS-MPC

In above FCS-MPC, two aspects need to improve. First, the voltage vector traversal algorithm would lead to high and unnecessary computational burden of microprocessor.

Second, the control accuracy of single vector output mode is low due to finite and deficient optional vectors, which leads to obvious current tracking error. And unfixed switching frequency would lead to scattered harmonics, which increases filter designing difficulty.

III. PROPOSED MPC STRATEGY

In order to solve the flaws of conventional FCS-MPC, three improvements are as follows. First, the proposed sector optimization method based on effective vector radiation range helps to directly determine the optimal vector without vector traversal. Second, the proposed virtual vector expansion method based on vector synthesis algorithm with fixed 1/4 & 1/2 & 3/4 duty cycle expands optional vectors from 8 to 44, and improves vector accuracy and system performance. Third, the modulated vector output mode is adopted to fix switching frequency and decrease current harmonics.

A. SECTOR OPTIMIZATION AND OPTIMAL VECTOR DETERMINATION

Different from conventional vector optimization with inevitable vector traversal, the proposed sector optimization method can directly determine the optimal vector without vector traversal. First, sectors are divided according to effective radiation range of 8 basic vectors. Second, reference vector is calculated according to current target, and its sector location is determined according to its abc-axis components state and subsector boundary function. Third, the optimal vector is determined according to reference vector sector location and effective vector radiation range.

1) SECTOR DIVISION METHOD

In Fig.3, the whole vector complex plane is divided into six sectors (I to VI) and each sector is divided into two subsectors (A and B) by vector vertical line, which is more conducive to determine effective vector radiation range, and different from conventional sector division method in Fig.2.

FIGURE 3. Proposed sector division method.

where V_2 to V_7 are located in the sector center; V_1 and V_8 are located in the complex plane origin.

For example, the hexagonal area P in Fig.3 is surrounded by vertical lines between zero vector and all non-zero vectors. When reference vector is located in area P, error between reference and zero vectors is the minimum compared with any other vectors. So, effective radiation range of zero vector is area P, and in other words, zero vector is the optimal basic vector in area P. And effective radiation range of other vectors is determined similarly.

2) OPTIMAL VECTOR DETERMINATION

In order to determine the optimal vector, reference vector (\(V^*(k)\)) that tracks target current perfectly is calculated, and sector location of \(V^*(k)\) is determined according to its abc-axis components state and subsector boundary function.

System current target is expressed as:

\[
\begin{align*}
    i_d^*(k+1) &= i_d^p \\
    i_q^*(k+1) &= i_q^p 
\end{align*}
\]

(7)

After substituting (7) into (3), \(V^*(k)\) is expressed as:

\[
\begin{align*}
    u_d^*(k) &= e_d(k) + \omega L_s i_d(k) - \frac{L_s}{T_s} (i_d^*(k+1)) \\
    - i_d(k) - R_s i_d(k) \\
    u_q^*(k) &= e_q(k) - \omega L_s i_q(k) - \frac{L_s}{T_s} (i_q^*(k+1)) \\
    - i_q(k) - R_s i_q(k) 
\end{align*}
\]

(8)

where \(u_{d,q}^*(k)\) are d-axis and q-axis components of \(V^*(k)\).
TABLE 2. Abc-axis components state and sector.

| Components | Sector | Components | Sector |
|------------|--------|------------|--------|
| $u_a^*(k) \leq 0$ | $u_a^*(k) \geq 0$ | IV |
| $u_b^*(k) \leq 0$ | $u_b^*(k) \geq 0$ | I |
| $u_c^*(k) \geq 0$ | $u_c^*(k) \leq 0$ | II |
| $u_a^*(k) \leq 0$ | $u_a^*(k) \geq 0$ | V |
| $u_b^*(k) \geq 0$ | $u_b^*(k) \leq 0$ | III |
| $u_c^*(k) \leq 0$ | $u_c^*(k) \geq 0$ | VI |

And abc-axis components ($u_a^*(k)$, $u_b^*(k)$ and $u_c^*(k)$) of $V^*(k)$ are obtained by inverse Clarke & Park transforms for $u_d^*(k)$ and $u_q^*(k)$, and expressed as:

$$
\begin{bmatrix}
  u_a^*(k) \\
  u_b^*(k) \\
  u_c^*(k)
\end{bmatrix}
= \begin{bmatrix}
  \cos \theta & \sin \theta \\
  \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) \\
  \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3)
\end{bmatrix}
\begin{bmatrix}
  u_d^*(k) \\
  u_q^*(k)
\end{bmatrix}
$$

(9)

Besides, abc-axis components state of $V^*(k)$ is related to its sector. For example, when $V^*(k)$ is in sector IV, its abc-axis components satisfy (10), and similarly in other sectors.

$$
\begin{align*}
  u_a(k) & \geq 0 \\
  u_b(k) & \leq 0 \\
  u_c(k) & \leq 0
\end{align*}
$$

(10)

And the sector of $V^*(k)$ is determined according to its abc-axis components state, and listed in TABLE 2.

Moreover, the subsector of $V^*(k)$ requires further determination according to subsector boundary function. Assume $V^*(k)$ is in sector IV shown in Fig. 4. If $V^*(k)$ satisfies boundary function (11), $V^*(k)$ is in subsector B and $V_5$ is determined as the optimal vector according to effective vector radiation range. Otherwise, $V^*(k)$ is in subsector A and zero vector is determined as the optimal vector.

$$
u_d^*(k) - \frac{1}{3}u_{dc} > 0
$$

(11)

And similarly in other sectors, the subsector of $V^*(k)$ is determined according to subsector boundary function, and listed in TABLE 3.

Therefore, the optimal vector is directly determined according to sector location of $V^*(k)$ and effective vector radiation range without vector traversal.

B. VIRTUAL VECTOR EXPANSION AND SUBSECTOR DIVISION

Only 8 optional vectors would lead to low control accuracy. In order to increase vector control accuracy, first, a virtual vector expansion method is proposed, which expands optional vectors from 8 to 44 by vector synthesis algorithm with fixed 1/4 & 1/2 & 3/4 duty cycle. Second, subsectors are divided according to effective radiation range of all 44 vectors to determine the optimal vector more efficiently. And sector location of $V^*(k)$ is determined by establishing subsector boundary functions. Third, the optimal vector is determined according to reference vector sector location and effective vector radiation range.

1) VIRTUAL VECTOR EXPANSION METHOD

Each virtual voltage vector ($V_{v\text{ir}}$) is synthesized by two adjacent basic voltage vectors with fixed duty cycle, and expressed as:

$$
V_{v\text{ir}} = \alpha_m V_m + \alpha_n V_n
$$

(12)
where $V_m$ and $V_n$ are two adjacent basic vectors; $\alpha_m$ and $\alpha_n$ are duty cycles of these two vectors.

And according to the volt-second balance theorem, $\alpha_m$ and $\alpha_n$ should satisfy:

$$\alpha_m + \alpha_n = 1 \quad (13)$$

Obviously, the more virtual vectors are expanded, the smaller vector control error would be. However, as virtual vectors expand, determining vector location becomes more and more difficult. So, in order to expand as many virtual vectors as possible and conveniently determine vector location, a vector synthesis algorithm with fixed 1/4 & 1/2 & 3/4 duty cycle is adopted, and 36 virtual vectors ($V_9$ to $V_{44}$) are expanded in Fig. 5.

The vector synthesis algorithm with fixed 1/2 & 1/2 duty cycle is that $\alpha_m = 1/2$ and $\alpha_n = 1/2$, namely, $V_m$ and $V_n$ operate for half period respectively. For example, virtual vector $V_9$ is synthesized by non-zero vectors $V_5$ and $V_7$, virtual vector $V_{15}$ is synthesized by non-zero vector $V_5$ and zero vector $V_1$, and they are expressed as:

$$\begin{align*}
V_9 &= \frac{1}{2}V_5 + \frac{1}{2}V_7 \\
V_{15} &= \frac{1}{2}V_5 + \frac{1}{2}V_1
\end{align*} \quad (14)$$

And the vector synthesis algorithm with fixed 1/4 & 3/4 duty cycle is that $\alpha_m = 1/4$ and $\alpha_n = 3/4$, or $\alpha_m = 3/4$ and $\alpha_n = 1/4$, namely, $V_m$ and $V_n$ operate for 1/4 or 3/4 period respectively. For example, virtual vector $V_{21}$ is synthesized by non-zero vectors $V_5$ and $V_7$, virtual vector $V_{33}$ is synthesized by non-zero vector $V_5$ and zero vector $V_1$, and they are expressed as:

$$\begin{align*}
V_{21} &= \frac{3}{4}V_5 + \frac{1}{4}V_7 \\
V_{33} &= \frac{1}{4}V_5 + \frac{3}{4}V_1
\end{align*} \quad (15)$$

And other virtual vectors are synthesized similarly. The optional vectors are expanded from 8 to 44, which increases vector control accuracy.

2) SUBSECTOR DIVISION AND OPTIMAL VECTOR DETERMINATION

With optional vectors expanding, there are more and more challenges to determine the optimal vector efficiently. The subsectors are divided according to effective radiation range of all 44 vectors. In Fig. 6, the whole vector complex plane is divided into six sectors (I to VI), and each sector is divided into nine subsectors (A to I) by vector vertical line.

For example, in Fig. 7, subsector C in sector IV is surrounded by vector vertical line of $l_1$, $l_2$, $l_3$ and $l_4$. Obviously, when $V^*(k)$ is in subsector C, the error between $V^*(k)$ and $V_{15}$ is the minimum compared with any other vectors. So, effective radiation range of $V_{15}$ is subsector C. Effective radiation range of other vectors is determined similarly, and listed in TABLE 4.

After determining effective radiation range of each vector, in order to seek the optimal vector, determination for sector location of $V^*(k)$ is required. With the same sector determination method above, its subsector is determined as follows.

Taking subsector C of sector IV in Fig. 7 for an example, according to effective vector radiation range determined...
TABLE 5. Subsector boundary functions (taking sector IV for example).

| sector | subsector | Boundary functions | Optimal vector |
|--------|-----------|--------------------|----------------|
| A      |           | $u_0^c(k) < 1/12u_{dc}$ | $V_{15}, V_5$ |
| B      |           | $u_0^c(k) > 1/4u_{dc}$ | $V_1$ |
| C      |           | $u_0^c(k) < -\sqrt{3}/3u_0^c(k) + 2\sqrt{3}/9u_{dc}$ | $V_{13}$ |
| D      |           | $u_0^c(k) > -\sqrt{3}/3u_0^c(k) + 2\sqrt{3}/9u_{dc}$ | $V_9$ |
| E      |           | $u_0^c(k) < -\sqrt{3}/3u_0^c(k) - 2\sqrt{3}/9u_{dc}$ | $V_{21}$ |
| F      |           | $u_0^c(k) > -\sqrt{3}/3u_0^c(k) - 2\sqrt{3}/9u_{dc}$ | $V_{14}$ |
| G      |           | $u_0^c(k) < \sqrt{3}/3u_0^c(k) + 2\sqrt{3}/9u_{dc}$ | $V_2$ |
| H      |           | $u_0^c(k) < \sqrt{3}/3u_0^c(k) + 2\sqrt{3}/9u_{dc}$ | $V_{22}$ |

**FIGURE 8.** Duty cycles of virtual vectors $V_9$ (a) and $V_{21}$ (b).

by vector synthesis algorithm with fixed $1/4$ & $1/2$ & $3/4$ duty cycle, boundary functions of subsector C are given as:

\[
\begin{align*}
I_1 & : x = 1/4u_{dc} \\
I_2 & : y = -\sqrt{3}/3x + 2\sqrt{3}/9u_{dc} \\
I_3 & : x = 5/12u_{dc} \\
I_4 & : y = \sqrt{3}/3x - 2\sqrt{3}/9u_{dc}
\end{align*}
\]  

(16)

**FIGURE 9.** Control block diagram of proposed MPC.

**FIGURE 10.** Simulation system.

When $V^*(k)$ is in subsector C, $u_{dq}^*(k)$ should satisfy:

\[
\begin{align*}
& u_{dq}^*(k) > 1/4u_{dc} \\
& u_{dq}^*(k) < -\sqrt{3}/3u_0^c(k) + 2\sqrt{3}/9u_{dc} \\
& u_{dq}^*(k) < 5/12u_{dc} \\
& u_{dq}^*(k) > \sqrt{3}/3u_0^c(k) - 2\sqrt{3}/9u_{dc}
\end{align*}
\]  

(17)

And similarly, the subsector of $V^*(k)$ is determined by subsector boundary functions, and listed in TABLE 5.

Therefore, the optimal vector is efficiently determined according to sector location of $V^*(k)$ and effective vector radiation range without vector traversal.

**C. MODULATED VECTOR OUTPUT MODE WITH FIXED SWITCHING FREQUENCY**

Each virtual vector is synthesized by two real basic vectors. Taking virtual vectors $V_9$ and $V_{21}$ for example, duty cycles of different power switches are shown in Fig. 8. Similarly, duty cycles of other virtual vectors could be obtained.
TABLE 6. System parameters.

| Symbol | Quantity                        | Value       |
|--------|---------------------------------|-------------|
| \(v\)  | Power grid voltage amplitude    | 311 V       |
| \(f\)  | Power grid frequency            | 50 Hz       |
| \(k_t\) | Transformer transformation ratio | 380/110     |
| \(L_s\) | AC-side inductance              | 8 mH        |
| \(R_s\) | Inductance internal resistance  | 0.1 \(\Omega\) |
| \(C\)  | DC-side capacitance             | 1100 \(\mu F\) |
| \(R_L\) | DC load equivalent resistance   | 100 \(\Omega\) |
| \(u_d^*\) | DC voltage reference           | 200 V       |
| \(i^*_q\) | Reactive current reference      | 0 A         |
| \(T_s\) | Simulation step                 | 0.1 ms      |

As shown in Fig. 8, multiple vectors are applied per control cycle, which leads to fixed switching frequency and lower current harmonics compared with conventional FCS-MPC.

D. SYSTEM CONTROL BLOCK DIAGRAM

The whole system control block diagram is shown as:

IV. SYSTEM SIMULATION

In order to verify feasibility and effectiveness of proposed MPC, a simulation system is established in Fig. 10, which mainly consists of 3P-2L-VSC system and its controllers. And its system parameters are listed in TABLE 6.

Three cases are carried out to compare system performance under the proposed MPC and conventional FCS-MPC, and expressed as:

A. SYSTEM STEADY PERFORMANCE COMPARISON AND ANALYSIS

Variation curves of system state variables \(i_d\), \(i_q\), and AC currents FFT analysis under proposed MPC and FCS-MPC are shown in Fig. 11 to Fig. 14 respectively when system operates stably at rated power.

Case A: System steady-state performance is compared and analyzed to verify the effectiveness of proposed virtual vector expansion method when system operates stably at rated power.

Case B: System transient performance is compared and analyzed to verify the effectiveness of proposed modulated vector output mode when DC load suddenly drops.

Case C: Algorithm computational burden are compared to verify the effectiveness of proposed sector optimization method.
In Fig. 11, blue active current target curve \( i^*_d \) is 9.2 A. Magenta curve \( i_d \) under proposed MPC tracks its target curve stably with the maximum error of about 2.1A. While cyan curve \( i_d \) under FCS-MPC tracks its target curve stably with the maximum error of about 3.2 A. Therefore, proposed MPC makes system have less active current error with a decrease by about 1.1 A compared with FCS-MPC.

In Fig. 12, blue reactive current target curve \( i^*_q \) is 0 A. Magenta curve \( i_q \) under proposed MPC tracks its target curve with the maximum error of about 2.0 A. While cyan curve \( i_q \) under FCS-MPC tracks its target curve with the maximum error of about 4.7 A. Therefore, proposed MPC makes system have less reactive current error with a decrease by about 2.7 A compared with FCS-MPC.

In Fig. 13, current fundamental wave amplitude and THD under proposed MPC are 9.20 A and 4.19 % respectively, and a few low-order harmonics exist. While in Fig. 14, current fundamental wave amplitude and THD under FCS-MPC are 9.20 A and 7.35 % respectively, and many low-order harmonics exist. Therefore, proposed MPC makes system have fewer current harmonics with a THD decrease by about 3.16 % compared with FCS-MPC.

Therefore, the proposed virtual vector expansion method makes system operate stably at rated power and have better steady-state performance with less current tracking error and harmonics compared with the 8 vectors selective output.

In Fig. 15, blue active current target curve \( i^*_d \) steps from 4.6 A to 9.2 A. Magenta curve \( i_d \) under proposed MPC tracks its new target curve in about 2.5 ms. While cyan curve \( i_d \) under FCS-MPC tracks its new target curve in about 5.1 ms. Therefore, proposed MPC makes system have shorter active current tracking response time with a decrease by about 2.6 ms compared with FCS-MPC.

In Fig. 16, blue reactive current target curve \( i^*_q \) is 0 A. Magenta curve \( i_q \) under proposed MPC tracks its target curve with the maximum error of about 2.0 A. While cyan curve \( i_q \) under FCS-MPC tracks its target curve with the maximum error of about 4.7 A. Therefore, proposed MPC makes system have less reactive current error with a decrease by about 2.7 A compared with FCS-MPC.

Variation curves of system state variables \( i_d, i_q \) under proposed MPC and FCS-MPC are shown in Fig. 15 and Fig. 16 respectively when DC load is stable at 100 Ω before 0.5 s, and then suddenly drops to 50 Ω.

In Fig. 15, blue active current target curve \( i^*_d \) steps from 4.6 A to 9.2 A. Magenta curve \( i_d \) under proposed MPC tracks its new target curve in about 2.5 ms. While cyan curve \( i_d \) under FCS-MPC tracks its new target curve in about 5.1 ms. Therefore, proposed MPC makes system have shorter active current tracking response time with a decrease by about 2.6 ms compared with FCS-MPC.

In Fig. 16, blue reactive current target curve \( i^*_q \) is 0 A. Magenta curve \( i_q \) under proposed MPC tracks its target...
curve with the maximum transient fluctuation of about 1.8 A. While cyan curve \((i_q)\) under FCS-MPC tracks its target curve with the maximum transient fluctuation of about 4.3 A. Therefore, proposed MPC makes system have better ability to stabilize reactive current with a transient fluctuation decrease by about 2.5 A compared with FCS-MPC.

Therefore, the modulated vector output mode makes system have better transient performance with faster active current tracking speed and less reactive current fluctuation compared with the conventional single vector output mode.

In summary, the steady-state and transient performance under two MPC algorithms are listed in TABLE 7 to highlight the enhanced outcomes of proposed MPC.

C. COMPUTATIONAL BURDEN COMPARISON

In order to evaluate algorithm computational burden of microprocessor, code execution time of proposed MPC and FCS-MPC in one cycle are counted in TABLE 8 respectively.

The proposed MPC takes microprocessor 32.9 µs in one cycle, while FCS-MPC takes microprocessor 34.7 µs under same system conditions.

Therefore, the proposed sector optimization method reduces algorithm computational burden of microprocessor compared with the conventional vector traversal algorithm.

V. SYSTEM EXPERIMENT

In order to further verify feasibility and effectiveness of proposed MPC in practical application, a system experiment platform based on dSPACE is built in Fig. 17.

The experiment platform mainly consists of 3P-2L-VSC system and dSPACE control platform. And two cases are expressed as:

Case A: System performance under the proposed MPC and conventional FCS-MPC is compared and analyzed to verify the effectiveness of virtual vector expansion method and modulated vector output mode when DC load suddenly drops.

Case B: The virtual vector expansion method is verified according to actual system state variables and switching states when system operates stably at rated power.

A. SYSTEM PERFORMANCE COMPARISON AND ANALYSIS

Experiment results of system state variables \(u_{dc}, e_a\) and \(i_a\) under proposed MPC and FCS-MPC are shown in Fig. 18 and Fig. 19 respectively when DC load suddenly drops.

In Fig. 18 and Fig. 19, blue curve \((e_a)\) and magenta curve \((i_a)\) under proposed MPC and FCS-MPC are sine curves with same phase and frequency (50 Hz) in steady-state period. However, curve \(i_a\) in Fig. 18 is thinner and smoother with the maximum pulsation of about 1.0 A compared with curve \(i_a\) in Fig. 19 with the maximum pulsation of about 1.5 A. Therefore, proposed MPC makes system operate stably with less current tracking error and harmonics compared with FSC-MPC.

When DC load suddenly drops, in Fig. 18, curve \(i_a\) tracks its new target stably in about 2 ms, cyan curve \((u_{dc})\) returns to 200 V again in about 55 ms with the maximum transient deviation of about 2.5 V. While in Fig. 19, curve \(i_a\) tracks its new target stably in about 3 ms, curve \(u_{dc}\) returns to 200 V again in about 135 ms with the maximum transient deviation of about 2.0 V.

Therefore, both strategies track control target in steady state and reach new target in a limited time. However, the proposed virtual vector expansion method and modulated vector output mode make system have better steady-state performance with less current tracking error and harmonics, and have better transient performance with faster current tracking and DC voltage recovery speed.
B. VIRTUAL VECTOR EXPANSION METHOD VERIFICATION

Experiment results of system state variables $i_d$, $i_q$, and switching states $s_a$, $s_b$ and $s_c$ under proposed MPC are shown in Fig. 20 when system operates stably at rated power.

In Fig. 20 (a), at point A, blue and magenta curves ($i_d$ and $i_q$) are about 9.3 A and 0.8 A. According to proposed MPC, reference vector $V^*(k)$ is located in subsector E of sector III, and virtual vector $V_{40}$ is determined as the optimal vector. So, basic vectors $V_1$ ($s_a = 0, s_b = 0$ and $s_c = 0$) and $V_4$ ($s_a = 0, s_b = 1$ and $s_c = 1$) should be output together, and operate for half cycle respectively. In Fig. 20 (b), in the control cycle corresponding to point A, the output switching states are “000–011–000”, which is consistent with analysis and calculation results according to values of $i_d$ and $i_q$.

Therefore, the proposed virtual vector expansion method is feasible and effective.

VI. CONCLUSION

According to above simulation and experiment results, we could draw the following conclusions.

1) The proposed virtual vector expansion method improves system steady-state performance with less current tracking error and harmonics compared with conventional FCS-MPC.

2) The proposed modulated vector output mode improves system transient performance with faster current tracking and DC voltage recovery speed compared with conventional single vector output mode.

3) The proposed sector optimization method reduces algorithm computational burden of microprocessor compared with conventional vector traversal algorithm.

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