A predictive control method for reducing power backflow in DC/AC matrix converter

Zhipeng Xia¹,a, Ping Jin ¹b*, Ling Chang ¹c

¹ College of Energy and Electrical Engineering Hohai University, Nanjing, Jiangsu, China

,aemail: 727565811@qq.com, cemail: 992828445@qq.com

b*email: jp81@hhu.edu.cn

Abstract: In recent years, DC/AC matrix converter with higher power density have become an attractive alternative to traditional voltage source converters. The traditional PI control has been employed to achieve accurate control, but its dynamic response and stability need to be improved. In this paper, a model predictive control (MPC) with reducing power backflow is introduced in an isolated DC/AC matrix converter with a loosely coupled high-frequency transformer (LCHFT). Prediction model and optimal function model are established to improve the dynamic response of the system and reduce the power backflow.

1. Introduction
With the development of smart grid, motor drives and electric vehicles, DC/AC converters are often used to realize the conversion and coordinated control of different forms of power [1]. There are two main kinds of DC/AC converters, isolated type with high-frequency transformers (HFT), and non-isolated type without HFT. Comparing with the latter, the former is more popular because of its enhanced reliability. In an isolated DC/AC matrix converter, a full bridge is usually employed to transfer the DC voltage to high-frequency AC (HFAC) voltage on the transformer’s primary side [2].

In isolated DC/AC matrix converters, PI control was adopted in [3] to achieve the basic operating functions of the system. Since the MPC can reduce the overshoot and improve the response speed, Wang [4] simulated typical MPC strategies based on constraint current vectors.

Considering that the power transmission between the front and back stages of an isolated DC/AC matrix converter is carried out through the phase shift Angle φ [5], and the duty ratio of the secondary side voltage is determined by the modulation factor m. Power backflow exists between front and rear stages, which reduces system efficiency and increases current stress.

In this paper, a predictive control method has better dynamic performances while achieving accurate control in an isolated DC/AC matrix converter. The optimal model among converter variables is established to minimize the current peak stress and power backflow of the converter.

2. Proposed topology and modes of operation

2.1. Proposed Topology
Fig. 1 shows the topology of the isolated DC/AC matrix converter with a LCHFT. The topology is mainly composed of a full bridge converter, a LCT and a 1-3MC. The full bridge converter consists of switches S1-S4. On the transformer’s primary side, $L_d$ represents the sum of auxiliary inductance and...
leakage inductance, and the turn ratio is 1:1. The 1-3MC consists of six groups of bidirectional switches $S_{xy}$ ($x=a, b, c$, $y=p, n$). Each group of bidirectional switches is composed of a pair of anti-parallel switches, upper one-way switch $S_{xy}^+$ and lower one-way switch $S_{xy}^-$. In the DC input side, $C_1$ represents the filter capacitor, $u_{dc}$ and $i_{dc}$ represent the voltage and current, respectively. In the AC output side, $C$ and $L$ represent the filter capacitor and inductance, $u_{ma}$, $u_{mb}$, $u_{mc}$ and $i_{la}$, $i_{lb}$, $i_{lc}$ represent the phase voltages and currents of matrix converter, $Z$ represents the load impedance, $u_{sa}$, $u_{sb}$, $u_{sc}$ and $i_{sa}$, $i_{sb}$, $i_{sc}$ represent the load voltages and currents, respectively. $u_1$ and $i_1$ represent the transformer primary voltage and current, $u_2$ and $i_2$ represent the transformer secondary voltage and current, respectively.

![Fig. 1](image1.png)

**Fig. 1** The main topology of the isolated DC/AC matrix converter.

### 2.2. Power backflow analysis

In the operation of the converter, the operating frequency of switches on both sides is the same. The voltage and phase applied to both ends of the series inductor are controlled by adjusting the phase shift angle $\phi$ between the front and rear stages. Since the turns ratio of the high frequency transformer is 1, the secondary side voltage can be converted to the original side. Fig. 2 shows voltage and current waveforms of primary and secondary side under phase shift control. In one switching cycle, there exists a state that the inductance current is opposite to the single voltage phase of the primary side. At this time, the transmission power is negative and power backflow occurs.

![Fig. 2](image2.png)

**Fig. 2** Voltage and current waveforms of primary and secondary side under phase shift control.

### 3. Model establishment

By establishing and discretizing the mathematical model of the output side, the feedback correction is introduced to obtain the predicted current components $i_{sdy}(k+1)$ and $i_{sqy}(k+1)$ of load side at $k+1$ time after introducing feedback correction. In order to make the predicted current closer to the given reference current, and make the current on the converter side smaller. The cost function of MPC is set to (1).

$$J=\min\left\{m_1\left[i_{sdy}(k+1)-i_{sdy}(k+1)\right]^2+n_1\left[i_{sqy}(k+1)-i_{sqy}(k+1)\right]^2\right\}+\min\left\{m_2\left[i_{ld}(k)\right]^2+n_2\left[i_{lq}(k)\right]^2\right\}$$

(1)

where $i_{sdy}(k+1)$ and $i_{sqy}(k+1)$ represent the reference currents in load side at $k+1$ time, $m_1$ and $m_2$ represent the output tracking control factors, $n_1$ and $n_2$ represent the constraint factors of the control
quantity. To track the voltage on the AC side and obtain the minimum converter current, the $d$- and $q$-axis minimum currents on the converter side can be expressed as (2) (3).

$$i_d = \frac{-cn_i l^s_d (k+1) + cn_i \{ -a[u_{ns}(k) - u_{ns}(k-1)] - bu_{ns}(k) + \frac{di_{ns}(k) - gi_{ns}(k) + f_s(k)}{n_s c^2 + m_s} \}}{n_s c^2 + m_s}$$

$$i_q = \frac{-cn_i l^s_q (k+1) - cn_i \{ -a[u_{ns}(k) - u_{ns}(k-1)] - bu_{ns}(k) - \frac{di_{ns}(k) + gi_{ns}(k) + f_s(k)}{n_s c^2 + m_s} \}}{n_s c^2 + m_s}$$

and

$$a = \frac{1}{\omega L}, \quad b = \frac{T}{L}, \quad c = \frac{T}{\omega CL}, \quad d = 1 - \frac{rT}{L}, \quad g = \left( \frac{\omega - \frac{1}{\omega CL}}{T} \right)$$

The corresponding transmission power $P$ of each switching cycle can be obtained by (5).

$$P = \frac{8a^2 u^2_n}{\pi^2 \omega_i L_i} - \frac{2N^2 u^2_n \cos \phi}{\pi \omega_i L_i}$$

where $\omega_s$ is the corresponding switching angular frequency, $U_n$ is the voltage amplitude of the transformer secondary side, $\phi$ is the voltage lead angle of the primary side of the transformer relative to the secondary side.

According to the power backflow formula in [5], the power backflow can be expressed as (6).

$$P_{\text{back}} = \frac{\sqrt{6\pi}N^2 U_n u^m_{\text{in}} \sin^2 \left( \frac{m \pi}{2} \right) + \sqrt{3} N^2 u^m_{\text{in}} \cos \frac{m \pi}{2} \cos \phi}{8\omega_i L_i} + \frac{N^2 u^m_{\text{in}}^2}{4\omega_i L_i}$$

It is necessary to find an improved parameter to minimize the current power backflow and the required transfer power. Therefore, this paper introduces an optimization value relation expressed as (7).

$$L = \min \left\{ P_{\text{back}} + \lambda (P - P^*) \right\}$$

where, $\lambda$ represents the weight coefficient and $P^*$ is the transmission power reference value.

Since the optimal value is related to the phase shift angle $\theta$ and the modulation coefficient $m$, the relationship between phase shift angle and modulation coefficient under minimum power backflow can be obtained as follows

$$\phi = \frac{2\sqrt{6\pi}U_n \cos \left( \frac{m \pi}{2} \right)}{NU_s}$$

3.1. Control diagram of the converter

The PI block diagram of the converter is given in Fig. 3(a). The three-phase voltages and currents on the output side of power frequency are measured, and the corresponding phase angles are obtained by using a phase-locked loop. The three-phase currents are converted to $i_{ld}$, $i_{ls}$ and the three-phase voltages to $u_{sd}$, $u_{sq}$ through the Park transformation. The modulation coefficient $m$ is obtained by combining the output value of the controller and the input current. The phase shift angle $\phi$ between full-bridge converter and matrix converter is set by the optimal model. The modulation coefficient and phase shift angle are sent into the SVM together to generate switching signals between the front and back stages.

The MPC block diagram of the converter is given in Fig. 3(b). The transformation of voltage and current is similar to PI. The load side prediction results are compensated by feedback correction. The minimized cost function is established, and the $m$ value is obtained correspondingly. The optimal value is the same as PI control.
Fig. 3  block diagram of HFLMI with (a) PI control and (b) MPC.

4. Simulation results

| Parameters                      | value     |
|---------------------------------|-----------|
| DC input voltage $U_{dc}$       | 80V       |
| Leakage inductance $L_k$        | 0.2mH     |
| Transformer ratio $N$           | 1:1       |
| Input filter capacitor $C_1$    | 3500uF    |
| Output filter inductor $L$      | 2.4mH     |
| Output filter capacitor $C$     | 10uF      |
| Load $R$                        | 10Ω       |
| Switching frequency $f$         | 10kHz     |
| Switching element               | MOSFET 4227 |

Three cases under PI control and MPC of the matrix converter are simulated by MATLAB/Simulink models, in which the corresponding parameters are listed in Tab 1. MOSFETs (4227) are used in both the H bridge and the 1-3MC. In the first case with PI control the modulation coefficient is set to 0.85, and the phase shift angle is selected according to the load power. In the second case with MPC, the phase shift angle is set to 90°, and the modulation coefficient is selected according to the load power. In the third case with MPC with power backflow optimization, the optimal value of the two is selected according to the relationship between the phase shift angle and the modulation coefficient derived in the previous section.

Fig. 4  The a-phase output voltage of the three cases under different control with (a) PI control and (b) MPC.
In case 3, the reference value of output current is changed from 1A to 2A under different control with (a) PI control and (b) MPC.

The a-phase output voltage of the three cases under different control are shown in Fig. 4. Under two kinds of control, the output waveform of case 1 has serious distortion compared with case 2 and case 3. Fig. 5 shows in case 3, the reference value of output current is changed from 1A to 2A under different control. MPC is faster than PI control. MPC has a shorter switching time than PI control. Fig. 6 shows the three cases corresponding to the transformer primary voltage, current and secondary voltage under different control. It can be seen that case 3 under the optimal function has smaller current peak stress than case 1 and case 2. The corresponding voltage and current calculation also results in lower power backflow.

5. Conclusions
This paper presented an isolated DC/AC matrix converter with a LCHFT. This converter eliminates capacitance in the intermediate stage and has high power density. A MPC-based tracking output current was proposed and compared with the conventional PI control and the power backflow was reduced by selecting the optimal value. The corresponding mathematical model and prediction model were established, and the cost function and optimal value were selected. The simulation with three cases under PI control and MPC were given. Under the change of reference current, MPC has better dynamic response and smaller overshoot. MPC with power backflow optimization has the minimum current peak stress and power backflow.
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