

# Finite States Model Predictive Direct Power Control for Phase Leg Faults Tolerant Operation of Bidirectional AC/DC Converter

Nan Jin, Leilei Guo, Chongyan Zhao, Zhifeng Dou, Guangzhao Cui  
College of Electric and Information Engineering  
Zhengzhou University of Light Industry  
Zhengzhou, China  
Jinnan@zzuli.edu.cn

**Abstract**—Based on the operation analysis of bidirectional AC/DC converter with leg faults, a power predictive model of four-switch three-phase (FSTP) in  $\alpha\beta$  coordinates is established. The finite states model predictive direct power control (MPDPC) method of fault-tolerant FSTP converter is designed for continuous operation, even if the phase leg of bidirectional AC/DC converter has a fault. According to the power predictive model and cost function, the optimal space voltage vector is selected to achieve flexible seamless switching between inverter and rectifier mode with direct power control. DC-link split capacitor voltage balance control is achieved by injecting a dc bias current into the faulty phase current. The proposed method does not need pulse width modulation signals and current control loop. It has the advantages of only minor calculations are required and it is easy to be implemented. The simulation and experiment results show good steady state and dynamic performance of proposed control method for bidirectional AC/DC converter with leg faults.

**Keywords**—Bidirectional AC/DC converter; power predictive model; FSTP converter; fault-tolerant MPDPC

## I. INTRODUCTION

The reliability and fault tolerant operation ability of the electric energy conversion system is the primary basis for the applications of the power electronics equipment [1]. Bidirectional AC/DC power converter is the key equipment in the hybrid microgrids, which connect the DC and AC microgrids [2]. The reliable and normal operation of the bidirectional power converter is the basis for the system reliability. However, full controlled switching devices of high power are used in occasions like high voltage, large capacity, high power density. The switching devices are prone to be destroyed by the transient voltage or current surges in switching process. It has great meaning to study the fault tolerant topology and control method of the bidirectional power converter to enhance the system reliability.

Studies have been carried out to maintain the continuous operation of the power converter, when there are switching faults in the power converter. A general PWM method for the control of four switch three phase inverter is presented in [3]. It provides a simple method to select the vector which synthesizes the output voltage, even when there are voltage oscillations in

the DC-link capacitors. The control scheme using Lyapunov function is implemented to track the inverter current and the spatial repetitive controller is also designed to eliminate the voltage unbalance of the dc-link split capacitors [4]. A predictive torque control is designed for the FSTP inverter-fed induction motor with the voltage balance control of the dc-link capacitors [5]. The voltage unbalance offset of the two dc-link capacitors is analyzed and controlled with model predictive control. These studies only consider the power conversion from DC-link to AC side and the fault-tolerant control of bidirectional power conversion have not been investigated.

Therefore, it is necessary to study the new control scheme of bidirectional AC/DC power converter with switching faults. Finite control states model predictive control (FCS-MPC) has been applied for power converters [6-8]. It does not need current control loop, PWM modulation and phase lock loop for the grid-tied applications. The paper [7] presents a model predictive direct power control (MPDPC) strategy for grid-connected inverter used in photovoltaic system. A system model is used to predict inverter behavior at each sampling instant. The optimal voltage vector is calculated with the cost function. In order to reduce the power ripple, the optimal switching states are applied in the next sampling period. The inverter works effectively in normal conditions. When there are switching faults in the power converter, the inverter cannot work continuously. A model predictive control method for the FSTP converter is proposed to reduce harmonics and power fluctuations under unbalanced grid voltages [9]. However, the dc-link split capacitor voltage balance control is not considered. The constraint of dc-link voltage constraint is designed for the cost function to achieve a central point of dc-link voltage offset suppression, which can reduce the risk of electrolytic capacitor failure for over-voltage operation [10]. But the constraint coefficient in the proposed cost function will influence the power quality and the current THD.

After the fault leg has been isolated by the connection switch, the bidirectional AC/DC converter is reconstructed as FSTP structure. Based on the working mechanism analysis, the fault-tolerant MPDPC is proposed to control FSTP converter. In this paper, by injecting the dc bias current to the phase current, the dc split capacitor voltage balancing control can be achieved, which makes the electrolytic capacitor work in a safe

operation. The flexible seamless working mode switching between the inverter and the rectifier mode of bidirectional power converter can be achieved. The control method can also directly realize direct power control without PWM modulation, which is easy to realize. Finally, the effectiveness of the control strategy is verified by simulation and experiments.

## II. FAULT TOLERANT MODEL OF BIDIRECTIONAL AC/DC CONVERTER

The fault-tolerant topology of the bidirectional power converter is shown in Fig. 1(a). The central point of the DC-link capacitor is connected with the bidirectional thyristors. When the power converter works normally, the thyristors are open. When there is a switching fault in one phase, such as in phase A, the thyristor  $TR_a$  is closed. Then the SSTP converter is reconstructed into FSTP converter, see in Fig. 1(b).

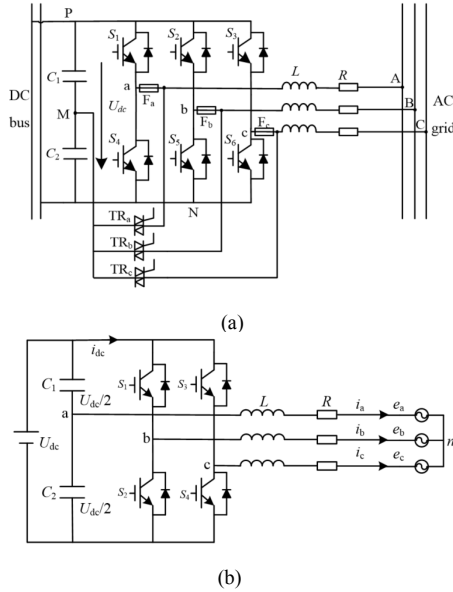


Fig. 1. Fault-tolerant topology of bidirectional AC/DC converter (a) fault-tolerant structure (b) FSTP structure with fault of phase A.

Fig. 1(b) shows the reconstruction structure of the bidirectional AC/DC converter with leg fault of phase A. It is connected to the grid through the filter inductor  $L$  and line resistance  $R$ . The DC side includes two capacitors  $C_1$  and  $C_2$  with equal value. The power conversion of bidirectional AC/DC converter contains rectifier mode and inverter mode. Taking the inverter mode as an example, the state equation of the  $\alpha\beta$  two phase stationary coordinates is obtained by transformation of (1).

$$L \frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + R \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \quad (1)$$

where  $i_\alpha, i_\beta, u_\alpha, u_\beta, e_\alpha, e_\beta$  are the  $\alpha\beta$  components of the converter output current, voltage and power grid voltage.

The expression of the output voltage and the switching state of the converter is obtained by the Clark transformation of (2):

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2U_{dc}}{9} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} 1-S_b-S_c \\ -1/2+2S_b-S_c \\ -1/2-S_b+2S_c \end{bmatrix} \quad (2)$$

Equation (1) can be discretized and the predictive current of  $t_{k+1}$  instant is as follows:

$$\begin{bmatrix} i_\alpha(k+1) \\ i_\beta(k+1) \end{bmatrix} = \frac{T_s}{L} \begin{bmatrix} u_\alpha(k) - e_\alpha(k) \\ u_\beta(k) - e_\beta(k) \end{bmatrix} + \left(1 - \frac{RT_s}{L}\right) \begin{bmatrix} i_\alpha(k) \\ i_\beta(k) \end{bmatrix} \quad (3)$$

where  $i_\alpha(k), i_\beta(k), u_\alpha(k), u_\beta(k), e_\alpha(k), e_\beta(k)$  are  $\alpha\beta$  components of the converter output current, voltage and the grid voltage at  $t_k$  instant.  $i_\alpha(k+1), i_\beta(k+1)$  are  $\alpha\beta$  components of predictive current value at  $t_{k+1}$  instant.

According to the instantaneous power theory, the predictive power model of  $t_{k+1}$  instant is:

$$\begin{cases} p(k+1) = e_\alpha(k)i_\alpha(k+1) + e_\beta(k)i_\beta(k+1) \\ q(k+1) = e_\beta(k)i_\alpha(k+1) - e_\alpha(k)i_\beta(k+1) \end{cases} \quad (4)$$

As shown in Fig. 1, the electrolytic capacitors  $C_1$  and  $C_2$  are in series connected in dc-link, where  $C_1 = C_2$ . Then the faulty phase current flow equally to two branches. The capacitor currents  $i_{dc1}$  and  $i_{dc2}$ , can be obtained by:

$$i_{dc1} = -i_{dc2} = \begin{cases} \frac{1}{2}i_a; \text{ leg a fault} \\ \frac{1}{2}i_b; \text{ leg b fault} \\ \frac{1}{2}i_c; \text{ leg c fault} \end{cases} \quad (5)$$

where  $i_{dc}$  is the dc-link current, shown in Fig. 2.

The capacitor voltages  $U_{dc1}$  and  $U_{dc2}$  change with currents as follows.

$$\begin{bmatrix} C \frac{dU_{dc1}}{dt} \\ C \frac{dU_{dc2}}{dt} \end{bmatrix} = \begin{cases} \begin{bmatrix} i_{dc} & -i_b & -i_c \\ i_{dc} + i_b + i_c & -i_b & -i_c \end{bmatrix} \begin{bmatrix} 1 \\ S_b \\ S_c \end{bmatrix}; \text{ leg a fault} \\ \begin{bmatrix} -i_a & i_{dc} & -i_c \\ -i_a & i_{dc} + i_a + i_c & -i_c \end{bmatrix} \begin{bmatrix} S_a \\ 1 \\ S_c \end{bmatrix}; \text{ leg b fault} \\ \begin{bmatrix} -i_a & -i_b & i_{dc} \\ -i_a & -i_b & i_{dc} + i_a + i_b \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ 1 \end{bmatrix}; \text{ leg c fault} \end{cases} \quad (6)$$

The derivative offset component of  $U_{dc1}$  and  $U_{dc2}$  can be shown as:

$$C \frac{d(U_{dc1} - U_{dc2})}{dt} = \begin{cases} -(i_c + i_b) = i_a; \text{ leg a fault} \\ -(i_a + i_c) = i_b; \text{ leg b fault} \\ -(i_a + i_b) = i_c; \text{ leg c fault} \end{cases} \quad (7)$$

Therefore, the offset component  $\Delta U_{dc}$  can be expressed by:

$$\Delta U_{dc} = \begin{cases} \frac{1}{C} \int_0^t i_a + (U_{dc1}(0) - U_{dc2}(0)); & \text{leg a fault} \\ \frac{1}{C} \int_0^t i_b + (U_{dc1}(0) - U_{dc2}(0)); & \text{leg b fault} \\ \frac{1}{C} \int_0^t i_c + (U_{dc1}(0) - U_{dc2}(0)); & \text{leg c fault} \end{cases} \quad (8)$$

where  $U_{dc1}(0)$ ,  $U_{dc2}(0)$  are initial voltage of  $C_1$  and  $C_2$ , respectively.

### III. FAULT TOLERANT MPDPC OF BIDIRECTIONAL AC/DC CONVERTER

For the selection of the optimal switching vector to realize direct power control, a cost function  $g$  is established to compare all predictive power values and select the voltage vector to make the cost function minimum. The sum of the absolute error value between predictive power and reference power is chosen as cost function:

$$g = |p_{ref} - p(k+1)| + |q_{ref} - q(k+1)| \quad (9)$$

where  $p_{ref}$ ,  $q_{ref}$  are active power and reactive power reference value.  $p(k+1)$ ,  $q(k+1)$  are power predictive value at  $t_{k+1}$  instant.

According to (7) and (8), the voltages of dc-link split capacitors are obtained by:

$$\begin{cases} U_{dc1} = \frac{U_{dc}}{2} + \frac{1}{2C} \int_0^t i_a dt + \frac{U_{dc1}(0) - U_{dc2}(0)}{2} \\ U_{dc2} = \frac{U_{dc}}{2} - \frac{1}{2C} \int_0^t i_a dt - \frac{U_{dc1}(0) - U_{dc2}(0)}{2} \end{cases} \quad (10)$$

The midpoint voltage  $U_{dc2}$  fluctuates around the  $U_{dc}/2$  with dc voltage offset  $-\Delta U_{dc}/2$ . In order to eliminate the dc-link midpoint voltage offset, a dc bias current  $\bar{i}_a$  can be injected into faulty phase current  $i_a$ . (10) can be revised as:

$$\Delta U_{dc} = U_{dc1} - U_{dc2} = \frac{1}{C} \int_0^t (i_a + \bar{i}_a) + [U_{dc1}(0) - U_{dc2}(0)] \quad (11)$$

Assume the phase current  $i_a = I_m \sin(\omega t)$ , the average value of dc voltage offset can be obtained.

$$\Delta \bar{U}_{dc} = \frac{1}{C} \int_0^t \bar{i}_a dt \quad (12)$$

In order to keep the balance control of the dc-link capacitor voltage, the average value of voltage deviation should be zero. The dc-link split capacitor voltage  $U_{dc1}$  and  $U_{dc2}$  are sampled in each sampling period. The average value of dc voltage offset can be obtained by using a lowpass filter. When there is a voltage offset, a corresponding dc current offset  $\bar{i}_a$  is generated by a proportional controller to eliminate the voltage unbalance.

$$\bar{i}_a = k_v \Delta \bar{U}_{dc} \quad (13)$$

where  $k_v$  is the proportional coefficient.

Hence, the current compensation component in  $\alpha\beta$  stationary frame can be obtained, using the Clark transformation.

$$\begin{bmatrix} \bar{i}_{aref} \\ \bar{i}_{\beta ref} \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2}{3}} \bar{i}_a \\ 0 \end{bmatrix} \quad (14)$$

In this design, the dc-link voltage balance term is not added to the cost function [10]. Therefore, the corresponding weighing factor is not needed in the cost function. And a proportional controller is added to realize the voltage balance control of the dc-link split capacitors. Thus, the reference power can be expressed as:

$$\begin{cases} p_{ref} = p_{ref} + e_a \bar{i}_{aref} \\ q_{ref} = q_{ref} + e_\beta \bar{i}_{\beta ref} \end{cases} \quad (15)$$

The fault-tolerant MPDPC structure of bidirectional AC/DC converter is shown in Fig. 2, with its flow diagram shown in Fig. 3.

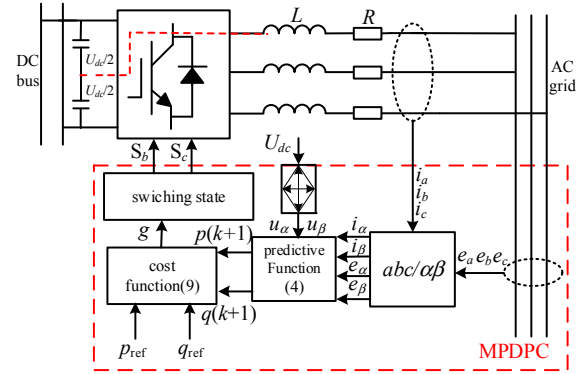


Fig. 2. Fault-tolerant MPDPC structure with fault of phase A.

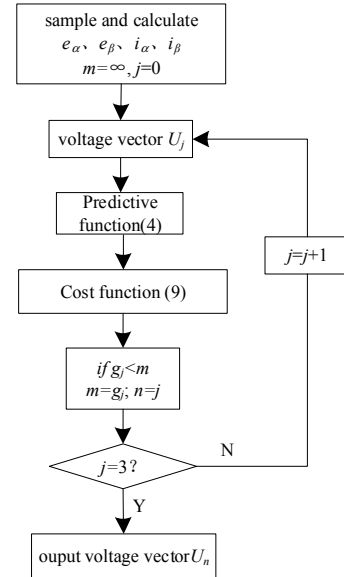


Fig. 3. Flow diagram of fault-tolerant MPDPC.

As shown in Fig. 2 and Fig. 3, power grid voltage and current  $e_a, e_b, e_c, i_a, i_b, i_c$  can be acquired by signal sampling circuits. After Clark transform, we can get  $e_\alpha, e_\beta, i_\alpha, i_\beta$ . Predictive function (4) outputs power predictive values  $p(k+1)$ ,

$q(k+1)$ . The voltage vectors can be evaluated through the cost function (9), then the switching state  $S_b, S_c$  is selected, which minimizes the cost function and is applied at  $t_{k+1}$  instant to achieve direct power control.

#### IV. SIMULATION RESULTS

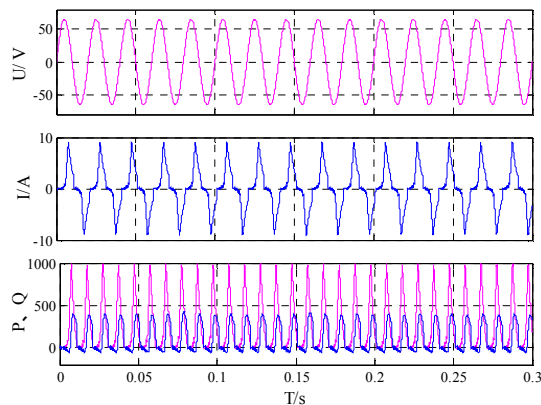
The simulink model of bidirectional AC/DC converter with fault tolerant MPDPC is built to verify the MPDPC strategy of fault-tolerant bidirectional AC/DC converter, and the system parameters are shown in Table I.

TABLE I. SYSTEM PARAMETERS OF BIDIRECTIONAL AC/DC CONVERTER

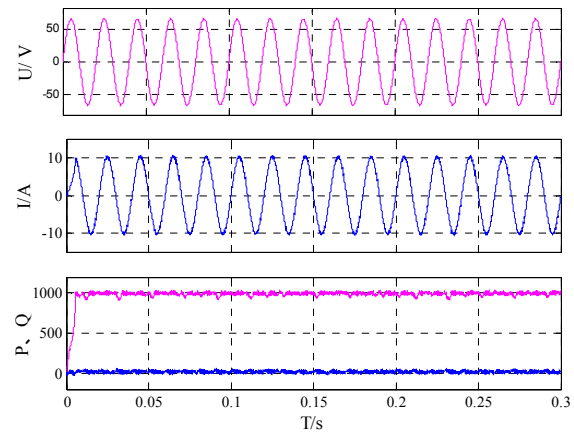
Symbol	System Parameters	Value
$U_{dc}$	DC-side voltage	300 V
$C$	Capacitance	1500 $\mu$ F
$L$	Filter inductance	20 mH
$e$	AC voltage	50 V

The fault occurs in the bridge leg of phase B, the reference active power is 1000 W and reactive power is 0. Fig. 4 shows grid voltage and current of phase A, active power and reactive power in the inverter mode. It can be seen from Fig. 4(a) that when leg fault occurs in the converter, the output current has serious distortion, active power fluctuates from 0 to 1 kW and reactive power vacillates between 0 and 400 Var, which shows that the converter does not work properly in inverter mode with traditional MPDPC. However, even if the bridge leg of phase B has a fault, the converter can run continuously under the control of proposed fault-tolerant MPDPC. The total harmonic distortion (THD) of grid current is 3.5% and it has better sinusoidal waveform. Besides, the output power is stable tracking reference power.

By changing the reference active power, the bidirectional AC/DC converter is switched from the inverter to the rectifier mode. The fault occurs in the bridge leg of phase B, the reference active power is -1000 W and reactive power is 0. Fig. 5 shows grid voltage and current of phase A, output active power and reactive power in the rectifier mode. The converter current and output power are distorted with traditional MPDPC, which cannot ensure normal operation, as shown in Fig. 5(a).



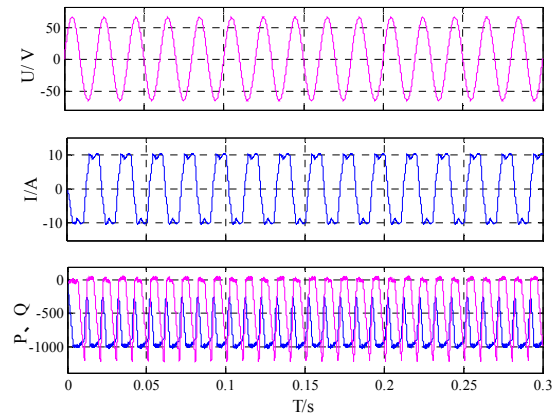
(a)



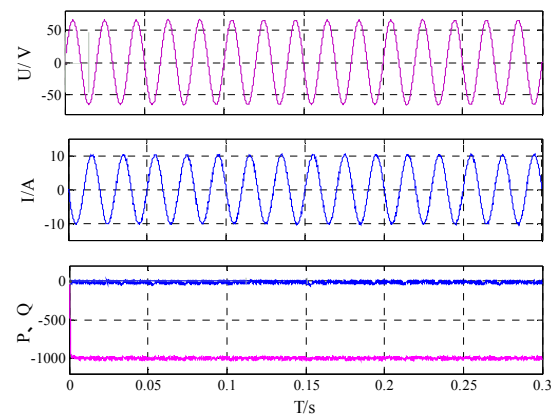
(b)

Fig. 4. Simulation results of MPDPC in inverter mode with leg faults of phase A (a) the traditional MPDPC (b) the proposed fault-tolerant MPDPC.

On the contrary, the grid current is sinusoidal with 3.3% THD and the output power keeps constant under the control of proposed fault-tolerant MPDPC.



(a)



(b)

Fig. 5. Simulation results in rectifier mode with leg faults of phase A (a) the traditional MPDPC (b) the proposed fault-tolerant MPDPC.

In order to verify the dynamic performance of the control strategy, the simulation is carried out as follows. The reference active power changes from 1000W (inverter mode) to -1000W (rectifier mode) at 0.1s instant and the simulation results are shown in Fig. 6. When the given power changes, the converter with fault-tolerant MPDPC achieves flexible seamless switching from the inverter to the rectifier mode and has good dynamic performance without surge peak transient impact.

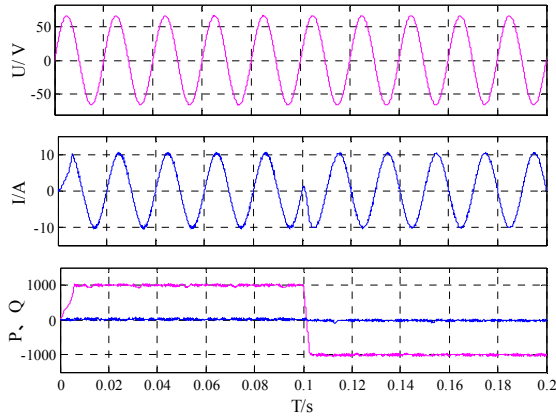


Fig. 6. Simulation results of switching between inverter and rectifier mode.

## V. EXPERIMENTAL VERIFICATION

The experimental platform is also setup to verify the effectiveness of the proposed control strategy, shown in Fig. 7. The experimental parameters are shown in Table I.

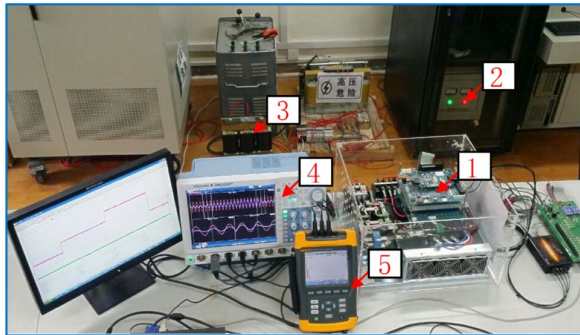


Fig. 7. Experimental setup (1. bidirectional AC/DC converter; 2. DC power source; 3. three-phase inductor; 4. oscilloscope; 5. power quality analyzer).

Fig. 8 and Fig. 9 show the steady state waveforms of bidirectional AC/DC converter in inverter mode with leg faults under traditional MPDPC and proposed fault-tolerant MPDPC. The following waveforms are included: voltage and current of phase A, three-phase current, active power and reactive power, unbalance degree of three-phase current, DC voltage and capacitor neutral point voltage and THD of three-phase current. Fig. 10 and Fig. 11 show experimental results in rectifier mode.

It can be seen from steady state waveforms that the grid current and output power of traditional MPDPC are highly distorted. The current THD is up to 56.6%, 25.9% and

unbalance degrees of three-phase current reach to 100%, 42.5% in inverter mode and rectifier mode, respectively. The waveforms show that when one bridge leg fault of bidirectional AC/DC converter happens, the traditional MPDPC can't realize effective control. However, it is amazing that the converter can work properly using proposed fault-tolerant MPDPC, even if the bridge leg breaks down. The current THD decreases to 3.0% in inverter mode and 2.6% in rectifier mode. The unbalance degrees are back to 2.3% in both inverter and rectifier mode. DC voltage and capacitor neutral point voltage remain stable throughout. The current THD and unbalance degrees are shown in Table II.

TABLE II CURRENT THD AND UNBALANCE DEGREES

Working Mode	THD	Unbalance Degrees
Traditional MPDPC in inverter mode	56.6%	100%
Proposed MPDPC in inverter mode	3.0%	2.3%
Traditional MPDPC in rectifier mode	25.9%	42.5%
Proposed MPDPC in rectifier mode	2.6%	2.3%

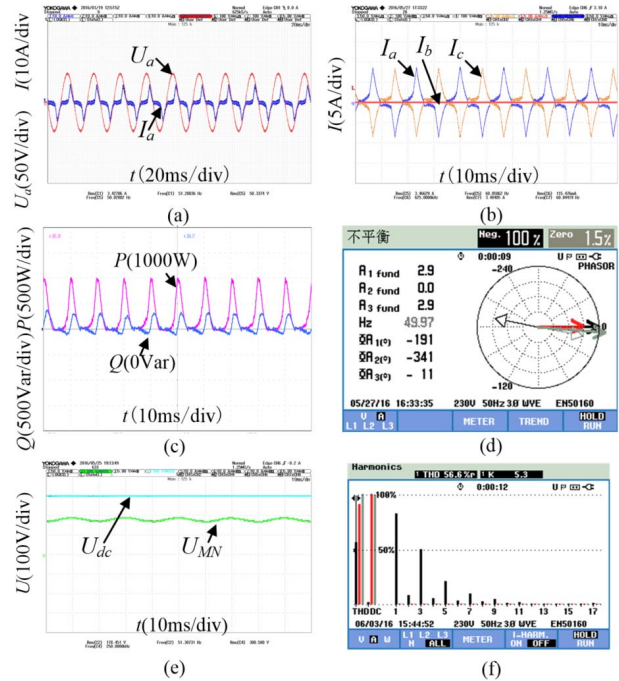


Fig. 8. Experimental results of traditional MPDPC in inverter mode with leg faults of phase B (a) voltage and current of phase A (b) three-phase current (c) active power and reactive power (d) unbalance degree of three-phase current (e) DC voltage and capacitor neutral point voltage (f) THD of three-phase current.

In order to verify the dynamic performance of the control strategy, the experiment is carried out as follows: the given active power steps from the 1kW (inverter mode) to -1kW (rectifier mode) at 0.05s. The experimental results are shown in Fig. 12. From the experimental results, it can be seen that the proposed fault-tolerant MPDPC shows better performance

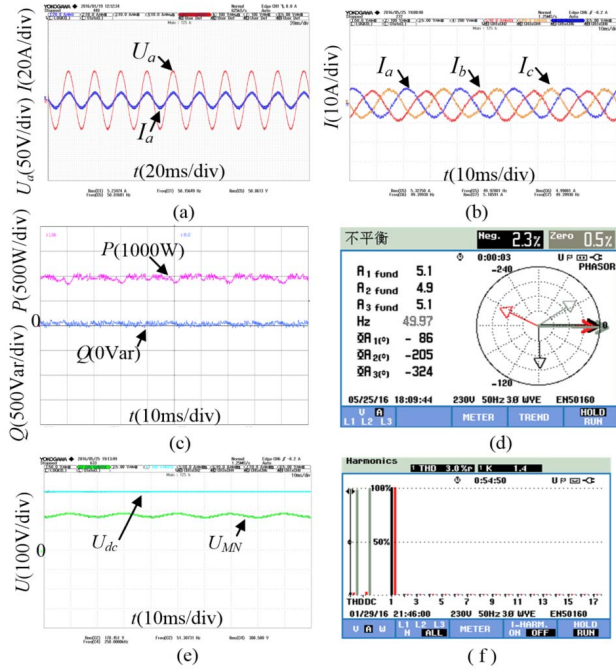


Fig. 9. Experimental results of proposed fault-tolerant MPDPC in inverter mode with leg faults of phase B (a) voltage and current of phase A (b) three-phase current (c) active power and reactive power (d) unbalance degree of three-phase current (e) DC voltage and capacitor neutral point voltage (f) THD of three-phase current.

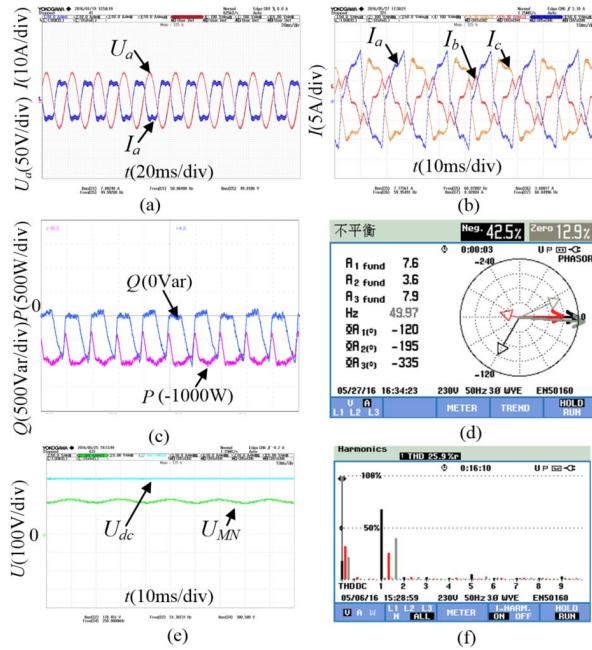


Fig. 10. Experimental results of traditional MPDPC in rectifier mode with leg faults of phase B (a) voltage and current of phase A (b) three-phase current (c) active power and reactive power (d) unbalance degree of three-phase current (e) DC voltage and capacitor neutral point voltage (f) THD of three-phase current.

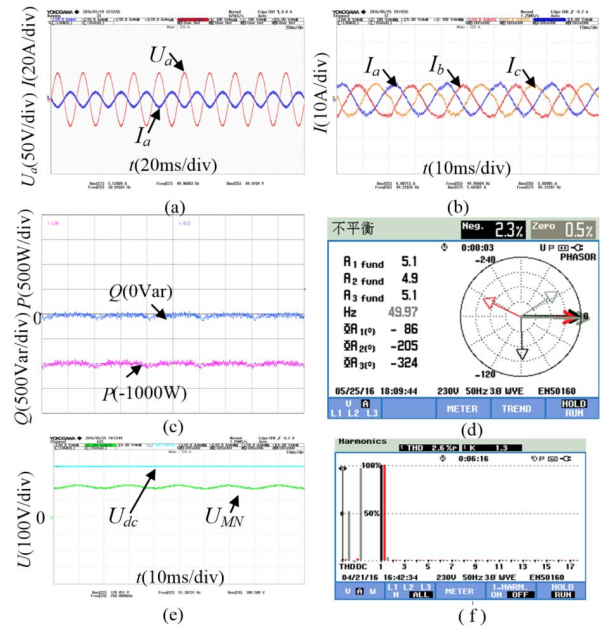


Fig. 11. Experimental results of proposed fault-tolerant MPDPC in rectifier mode with leg faults of phase B (a) voltage and current of phase A (b) three-phase current (c) active power and reactive power (d) unbalance degree of three-phase current (e) DC voltage and capacitor neutral point voltage (f) THD of three-phase current.

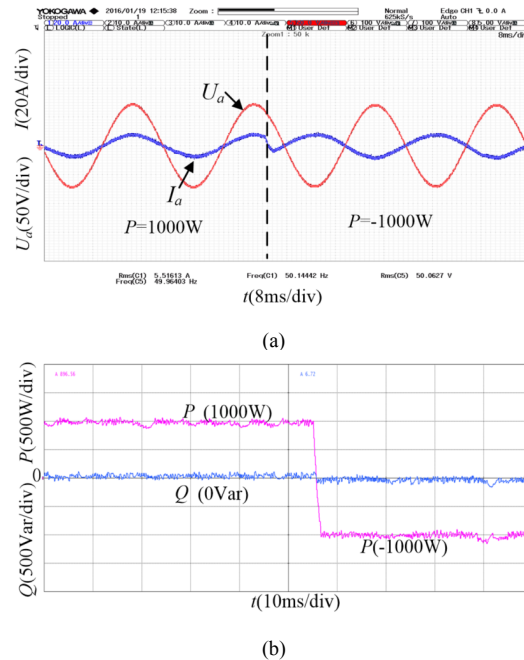


Fig. 12. Experimental dynamic waveforms of proposed fault-tolerant MPDPC with reference active power steps from 1000W to -1000W (a) voltage and current of phase A (b) active power and reactive power of converter.

in comparison with traditional MPDPC and can ensure normal operation of converter with leg faults.

Fig. 12 shows that when the reference active power of the proposed fault-tolerant MPDPC changes, the output power reaches to the new value after about 0.2ms without current surge and power fluctuations and other transient impact. Three-phase current is sinusoidal and the flexible seamless switching between inverter and rectifier mode can be realized. The output power of converter keeps constant with the reference value.

## VI. CONCLUSIONS AND FUTURE WORK

This paper presents fault-tolerant power predictive model of bidirectional AC/DC converter and designs the fault-tolerant MPDPC method with dc-link voltage balancing for the converter with phase leg fault. The following conclusions are obtained by simulation and experiment: FSTP structure is reconstructed after leg fault isolation of bidirectional AC/DC converter. The converter output current waveform of the proposed fault-tolerant MPDPC is sinusoidal and has good steady state and dynamic performance. However, the traditional MPDPC cannot work effectively. The proposed control method does not need double loop control and PWM modulation signals, which is easy to realize. Finally, the dc-link split capacitor voltage balancing control is achieved by injecting a dc bias current to the reference current. Compared with the method in [10], the dc-link voltage balancing coefficient is not needed in cost function which will enhance the power quality. The simulation and experiment results show that when the given reference power changes, the fault-tolerant working mode of inverter and rectifier can be switched smoothly with good dynamic performance.

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