A Fault Tolerant Strategy Based on Model Predictive Control for Full Bidirectional Switches Indirect Matrix Converter

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ABSTRACT

This paper proposes an open-switch fault tolerant strategy based on the model predictive control for a full bidirectional switches indirect matrix converter (FBS-IMC). Compared to the conventional Indirect Matrix Converter (IMC), the FBS-IMC can provide healthy current path when open-switch fault is occurred. To keep the continuous operation, the fault tolerant strategy is developed by means of reversing the DC-link voltage polarity regardless of the faulty switch location in the rectifier or inverter stage. Therefore, the proposed control strategy can maintain the same input and output performances during the faulty condition as the normal condition. The simulation results are given to verify the effectiveness of the proposed strategy.

Keyword: full bidirectional switches indirect matrix converter, fault tolerant, predictive control for IMC.

1. INTRODUCTION

The matrix converter (MC) is a direct AC/AC converter which has several advantages such as sinusoidal input and output current waveforms, bidirectional power flow, controllable input power factor and no bulky intermediate energy storage. Due to the absence of intermediate energy storage on DC-link, MCs have longer life time and more compact design compared to back-to-back converters with equivalent power ratings. With these advantages, MCs have become attractive to many applications such as wind power generation [1], induction motor drive [2], and power supply [3].

The applications in [1]–[3] often require a high reliability and robustness against the power switch failures. Therefore, the control method with fault tolerant capability is necessary to improve the system reliability.

In [4], the full bidirectional switches indirect matrix converter (FBS-IMC) is presented by adding six additional switches into the inverter stage as backup switch to improve the fault-tolerant strategy capacity of the conventional Indirect Matrix Converter (IMC). However, the fault tolerant strategy in [4] only treats the open-switch fault in the inverter stage of the FBS-IMC. To fulfill fault tolerant capacity of the FBS-IMC, this paper proposes a fault tolerant strategy based on the Model Predictive Control (MPC) in [5] to maintain the continuous operation of the system irrespective of the open-switch fault location in the rectifier or inverter stage. The proposed control strategy is implemented by reversing the DC-link voltage polarity when the open-switch fault is detected. The effectiveness of the proposed control strategy is verified by simulation results.

2. MODEL PREDICITVE CONTROL

In MPC, the system model is used to predict the future behaviors of the control variables. Based on the system model, the cost function is defined as the absolute error between the control variable references and their predicted value. After that, the switching state which minimizes the cost function is selected to control the converter in the next sampling period. Our control objectives are tracking the output current reference and achieving unity input power factor for FBS-IMC. The input power factor is indirectly controlled by means of the instantaneous input reactive power.

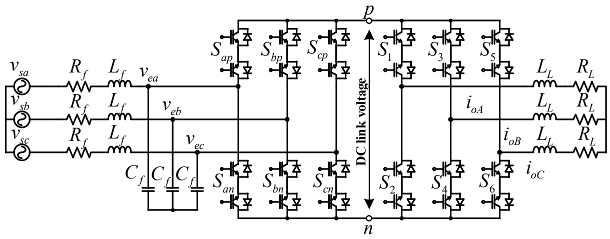


Fig. 1. The topology of FBS-IMC

TABLE 1. The valid switching states of the rectifier stage

No.	S_{ap}	S_{bp}	S_{cp}	S_{an}	S_{bn}	S_{cn}	v_{DC}
1	1	0	0	0	1	0	v_{ab}
2	1	0	0	0	0	1	v_{ac}
3	0	1	0	1	0	0	v_{ba}
4	0	1	0	0	0	1	v_{bc}
5	0	0	1	1	0	0	v_{ca}
6	0	0	1	0	1	0	v_{cb}
7	1	0	0	1	0	0	0
8	0	1	0	0	1	0	0
9	0	0	1	0	0	1	0

TABLE 2. The valid switching states of the inverter stage

No.	S_1	S_3	S_5	S_2	S_4	S_6	v_{AB}	v_{BC}	v_{CA}
1	1	1	0	0	0	1	0	v_{DC}	$-v_{DC}$
2	1	0	0	0	1	1	v_{DC}	0	$-v_{DC}$
3	1	0	1	0	1	0	v_{DC}	$-v_{DC}$	0
4	0	0	1	1	1	0	0	$-v_{DC}$	v_{DC}
5	0	1	1	1	0	0	$-v_{DC}$	0	v_{DC}
6	0	1	0	1	0	1	$-v_{DC}$	v_{DC}	0
7	1	1	1	0	0	0	0	0	0

2.1. Input and Output Current Predictions

The discrete state-space equation for the input side is obtained from Fig. 1:

$$\begin{bmatrix} i_s^{k+1} \\ v_e^{k+1} \end{bmatrix} = C \begin{bmatrix} i_s^{k} \\ v_e^{k} \end{bmatrix} + D \begin{bmatrix} i_e^{k} \\ v_s^{k} \end{bmatrix}, \tag{1}$$

where i_s is the source current and v_e is the input voltage, respectively. In (1), matrices C and D are calculated as follows:

$$C = e^{AT_s},\ D = A^{-1}(C - I)B,$$

$$A = \begin{bmatrix} -1/L_f & -R_f/L_f \\ 0 & 1/C_f \end{bmatrix},\ B = \begin{bmatrix} 1/L_f & 0 \\ 0 & -1/C_f \end{bmatrix},$$

where v_s is the source voltage; R_f, L_f, and C_f are the resistance, inductance and capacitance of the input filter, respectively. Similarly, the discrete state-space equation of the output side is obtained as follows:

$$i_o^{k+1} = \left(1 - \frac{R_L T_s}{L_L}\right) i_o^k + \frac{T_s}{L_L} v_o^k, \tag{2}$$

where i_o and v_o are the output current and voltage; R_L and L_L are the resistance and inductance of the output side, respectively. By using (1) and (2), the source and output currents in the next sampling period $(k+1)^{th}$ are predicted in every sampling period k_{th}.

2.2. Cost function minimization

The cost function g for each switching state is defined as the absolute value of the input instantaneous reactive power error and output current error:

$$g^{k+1} = \nabla q^{k+1} + \lambda.\Delta i_o^{k+1}, \quad (3)$$

where Δq and Δi_o are calculated as follows:

$$\Delta q^{k+1} = \left|0 - (v_{s\alpha}^{k+1} i_{s\beta}^{k+1} - v_{s\beta}^{k+1} i_{s\alpha}^{k+1})\right|,$$
$$\nabla i_o^{k+1} = | i_{o\alpha}^{*} - i_{o\alpha}^{k+1} | + | i_{o\beta}^{*} - i_{o\beta}^{k+1} |,$$

and λ is the weighting factor, $v_{s\alpha}^{k+1}, v_{s\beta}^{k+1}, i_{s\alpha}^{k+1}$ and $i_{s\beta}^{k+1}$ are the source voltages and currents in $\alpha\beta$ coordinates at $(k+1)^{th}$ sampling period; $i_{o\alpha}^{k+1}$, $i_{o\beta}^{k+1}$, $i_{o\alpha}^{*}$ and $i_{o\beta}^{*}$ are the load currents and their references in $\alpha\beta$ coordinates at $(k+1)^{th}$ sampling period, respectively. At each sampling time, all the combination valid switching states in Table 1 and 2 are used to calculate the cost function in (3), and the switching state that minimizes the cost function is applied in the next sampling period.

3. PROPOSED CONTROL STRATEGY

When the open-switch fault occurs, the faulty switch is rapidly detected and isolated from the power circuit. After that, the fault tolerant strategy is applied to keep the continuous operation of the FBS-IMC and avoid any damages caused by overvoltage or overcurrent. For more specific, the proposed control strategy is analyzed in two cases:

Case 1 when the driving signal of faulty switch is 0:

Noting that the power switch is turned on when its driving signal is 1, and turned off when its driving signal is 0. Therefore, the operation of FBS-IMC is not affected by open-switch fault when the driving signal is 0 regardless of the faulty switch location in rectifier or inverter stage. In this case, the proposed control strategy keeps the same driving signals for all switches as the conventional MPC.

For example, the open-switch fault occurs in the switch S_{bp}, and the present switching states for the rectifier stage is No. 1 in Table 1 and for the inverter stage is No. 2 in Table 2, respectively. It is clear that the operation of the converter is not affected by the faulty switch, and the current flows consistently between the source and the load as shown in Fig. 2. The driving signals of all switches are kept the same as those in the conventional MPC:

$$\begin{cases} G_{S_{ap}}^f = G_{S_{ap}} \\ G_{S_{an}}^f = G_{S_{an}} \\ G_{S_{bp}}^f = G_{S_{bp}} \end{cases}, \begin{cases} G_{S_{bn}}^f = G_{S_{bn}} \\ G_{S_{cp}}^f = G_{S_{cp}} \\ G_{S_{cn}}^f = G_{S_{cn}} \end{cases}, \begin{cases} G_{S_1}^f = G_{S_1} \\ G_{S_2}^f = G_{S_2} \\ G_{S_3}^f = G_{S_3} \end{cases}, and \begin{cases} G_{S_4}^f = G_{S_4} \\ G_{S_5}^f = G_{S_5} \\ G_{S_6}^f = G_{S_6} \end{cases}, \quad (4)$$

where G is the driving signal of the conventional MPC, and G^f is the driving signal of the proposed control strategy.

Case 2 when the driving signal of the faulty switch is 1:

In this case, the faulty switch is always opened even though its driving signal is 1. Therefore, the proposed control strategy controls all switches by means of exchanging the driving signal between the upper and lower switches in the same leg.

Firstly, we consider that open-switch fault occurs in the rectifier stage. Let's assume that the fault occurs in the switch S_{ap} and the present switching states for the rectifier stage is No. 1 in Table 1 and for the inverter stage is No. 2 in Table 2,

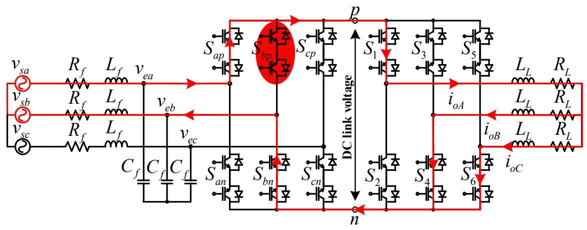


Fig. 2. Current path when the fault occurs in the switch S_{bp}.

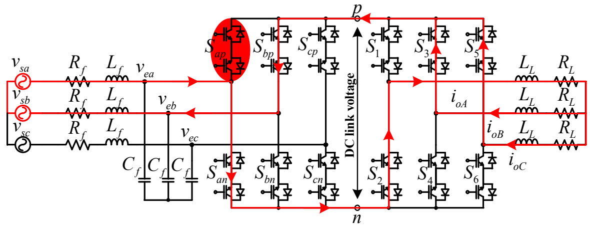
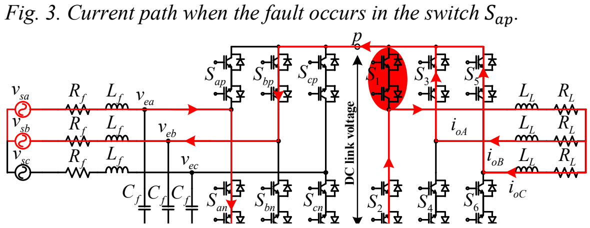


Fig. 3. Current path when the fault occurs in the switch S_{ap}.



respectively. When the conventional MPC is applied under the normal condition, the current flows the same path as shown in Fig. 2. However, when the fault occurs in the switch S_{ap}, the current cannot flow from the source to the load by the current path in Fig. 2 because there is no connection between input phase a and DC-link polarity p. After the proposed control strategy is activated, the driving signal of the faulty switch S_{ap} is quickly turned off, and the current path is modified as shown in Fig. 3. Compared to the conventional MPC, the proposed control strategy can keep the continuous operation of the FBS-IMC without affecting the input and output performances. The driving signals of all switches are modified as follows:

$$\begin{cases} G_{S_{ap}}^f = 0 \\ G_{S_{an}}^f = G_{S_{ap}} \\ G_{S_{bp}}^f = G_{S_{bn}} \end{cases}, \begin{cases} G_{S_{bn}}^f = G_{S_{bp}} \\ G_{S_{cp}}^f = G_{S_{cn}} \\ G_{S_{cn}}^f = G_{S_{cp}} \end{cases}, \begin{cases} G_{S_1}^f = G_{S_2} \\ G_{S_2}^f = G_{S_1} \\ G_{S_3}^f = G_{S_4} \end{cases}, and \begin{cases} G_{S_4}^f = G_{S_3} \\ G_{S_5}^f = G_{S_6} \\ G_{S_6}^f = G_{S_5} \end{cases} \quad (5)$$

Secondly, we consider that open-switch fault occurs in the inverter stage. Let's assume that the fault occurs in the switch S_1 and the present switching states for the rectifier stage is No. 1 in Table 1 and for the inverter stage is No. 2 in Table 2, respectively. The proposed control strategy achieves the continuous operation by turning off driving signal of the switch S_1, and modifying the current path as shown in Fig. 4. The driving signals of all switches are modified as follows:

$$\begin{cases} G_{S_{ap}}^f = G_{S_{an}} \\ G_{S_{an}}^f = G_{S_{ap}} \\ G_{S_{bp}}^f = G_{S_{bn}} \end{cases}, \begin{cases} G_{S_{bn}}^f = G_{S_{bp}} \\ G_{S_{cp}}^f = G_{S_{cn}} \\ G_{S_{cn}}^f = G_{S_{cp}} \end{cases}, \begin{cases} G_{S_1}^f = 0 \\ G_{S_2}^f = G_{S_1} \\ G_{S_3}^f = G_{S_4} \end{cases}, and \begin{cases} G_{S_4}^f = G_{S_3} \\ G_{S_5}^f = G_{S_6} \\ G_{S_6}^f = G_{S_5} \end{cases} \quad (6)$$

4. SIMULATION RESULTS

In order to verify the effectiveness of the proposed control strategy, the simulation is carried out by using PSIM software. The simulation parameters are listed in Table 3. The load current reference is set to be 10A/50Hz for all simulations.

Fig. 5 shows the performance of the conventional MPC for the FBS-IMC under the normal condition. As shown in Figs.

TABLE 3. Simulation parameters

Source voltage (V_{RMS})	$220V$
Input frequency	$60Hz$
Input filter parameters	$R_f = 5\Omega;\ L_f = 130\mu H; C_f = 40\mu F$
Load parameters	$R_L = 10\Omega; L_L = 35mH$
Output frequency	$50Hz$
Sampling period	$25\mu s$

5(a) and (b), the source and load currents are balanced sinusoidal. The positive DC-link voltage is maintained as shown in Fig. 5(c). Fig. 5(d) shows that the phase a source current and voltage are in phase, which means that the unity power factor is achieved.

Fig. 6 shows the performance of the FBS-IMC when the open-switch fault occurs in the switch S_{ap} of the rectifier stage. When the conventional MPC is applied in the first half in Fig. 6, the source and load currents are severely deteriorated and overvoltage is occurred on the DC-link, which may damage the power circuit. In contrast, when the proposed control strategy is activated in the latter half in Fig. 6, the source and load currents are balanced sinusoidal as shown in Fig. 6(a) and (b) while the overvoltage on the DC-link is avoided as shown in Fig. 6(c). The polarity of the DC-link voltage is reversed in some periods due to exchanging the driving signals between the upper and lower switches. The latter half of Fig. 6(d) shows that the phase a source current and voltage are in phase, which means that the unity power factor is achieved when the proposed control strategy is activated.

Fig. 7 shows the performance of the FBS-IMC when the open-switch fault occurs in the switch S_1 of the inverter stage. When the conventional MPC is applied, the performance of the source and load currents are severely deteriorated, as shown in the first half of Fig. 7. However, when the proposed fault tolerant strategy is activated in the latter half of Fig. 7, the source and load currents are kept balanced sinusoidal. Similarly, when the fault occurs in the rectifier stage, the proposed control strategy reverses the polarity of the DC-link voltage in some periods to keep the continuous operation of the FBS-IMC. The latter half of Fig. 7(d) shows that the phase a source current and voltage are in phase, which means that the unity input power factor is achieved when the proposed control strategy is activated. From Figs. 5 to 7, it is clear that the proposed control strategy can maintain the same input and output performances during the faulty condition as the normal condition regardless of the faulty switch location in the rectifier or inverter stage.

5. CONCLUSION

This paper proposed an effective open-switch fault tolerant strategy based on MPC for the FBS-IMC. By reversing the DC-link voltage polarity, the proposed control strategy provides the current path to keep the continuous operation of the converter regardless of the faulty switch on the rectifier or inverter stage. Moreover, compared to the previous methods, the proposed control strategy can achieve a good performance in both the input and output side during the faulty condition as the normal condition. The effectiveness of the proposed control strategy is verified by the simulation results.

6. ACKNOWLEDGMENTS

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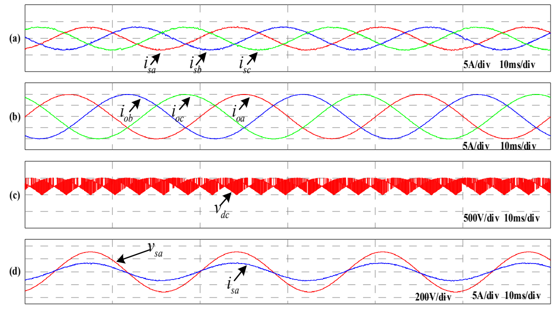

Fig. 5. Performance of the conventional MPC under the normal condition: (a) the source currents, (b) the load currents, (c) the DC-link voltage, (d) the source voltage and current of phase a

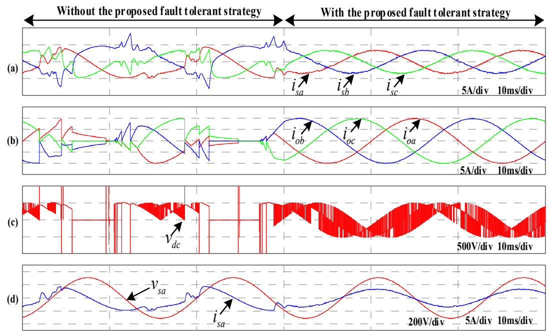

Fig. 6. Performance of the conventional MPC and the proposed control strategy when the fault occurs in the switch S_{ap}: (a) the source currents, (b) the load currents, (c) the DC-link voltage, and (d) the source voltage and current of phase a.

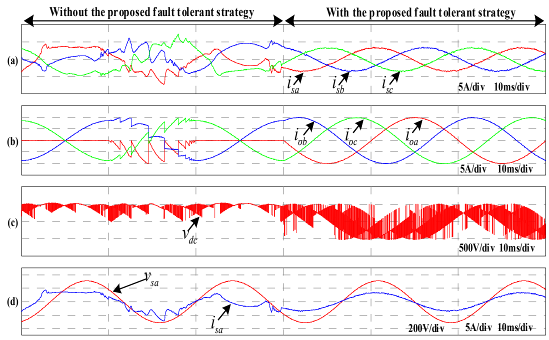

Fig. 7. Performance of the conventional MPC and the proposed control strategy when the fault occurs in the switch S_1: (a) the source currents, (b) the load currents, (c) the DC-link voltage, and (d) the source voltage and current of phase a.

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