Matrix Converter Open Circuit Fault Diagnosis with Asymmetric One Zero SVM

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***Abstract*—An open-circuit fault detection and diagnosis strategy for a direct matrix converter is proposed in this paper. The current recirculating path during an open circuit condition is considered in detail with the aim of contributing more expert knowledge to the fault detection system for matrix converter. Simulation results are presented demonstrate the open circuit fault behavior of matrix converter. This expert knowledge is extremely important for the fault detection system to avoid false diagnosis. This work leads to the presentation of a reliable and fast fault detector for the Matrix Converter.**

***Index Terms*—Fault Detection, Diagnosis, Matrix Converter, Clamp Circuit, Current Cancellation.**

I. Introduction

Matrix Converters (MC) continue to attract research attention due to the many advantages of the circuit such as the possibility of good power density[1], controllable input power factor, and the removal of the need for DC-Link capacitors [2]. Therefore, matrix converters are considered to be the alternative topology for AC-AC power conversion in many applications such as aerospace, electrical vehicles, and military applications [1]. Modulation methods and commutation techniques for matrix converters have been well developed in the literature [1], [3], [4]. Comparisons of the reliability between the matrix converter and other AC-AC converter topologies have also been considered [5], [6].

This paper focuses on the impact and detection of open circuit device faults. It is inevitable that a open circuit fault will occur during the systems lifetime. In order for continued operation, fast and reliable fault diagnosis methods are essential to minimize the hazard of over-voltage or over-current condition. The fault detection and diagnosis methods in power electronics proposed in the literature can be mainly divided into two categories: the signal processing-based [7] and the analytical model-based methods [8]–[13]. In [7], a Fast Furrier Transformation (FFT) is used to analyze the spectral components in the output current, but this method cannot locate the fault to the exact bidirectional switch because the spectral components of each faulty device in one output phase are similar.

Considering the analytical model-based fault diagnosis methods, in [8], the matrix converter output voltage is captured by three additional voltage sensors and used for fault detection purpose, which can locate the fault to a particular output phase rather than to one bidirectional switch. The work presented in [9] improves the output error voltage method by implementing nine modulated error voltages to locate the fault to one switch. In [10], a MC fault diagnosis method is proposed which relies on the reduction of the MC output currents with specific conditions satisfied such as the input-output voltage space vectors and power switches duty-cycle limitation under the Optimized Alesina-Venturini (OAV) modulation method. However, the integration of output currents will slow down the fault detection process. In [11], a fault detection method based on the clamp circuit capacitor current measurement is proposed. An additional current sensor is used in this method and the fault detection process is slowed down by the integration of the clamp circuit current. In [13], a fault diagnosis method, relying on the load currents decreasing to zero, is proposed under model predictive control (MPC) of matrix converters. This method needs 1.4ms to locate the faulty switch. [12] proposes a fault diagnosis method which relocates the three output current sensors ahead of the clamp circuit to directly measure the matrix converter output currents within three different zero vectors. However, the zero vectors duty-cycle are extremely small and hard to capture in high modulation ratio occasion.

This paper presents a novel, fast and reliable fault detection and diagnosis method which can locate a fault within two modulation periods and does not require additional hardware. An asymmetric SVM switch pattern is used which applies four active vectors and one zero vector. The output current of MC is captured five times in one modulation period. In addition, the expert knowledge of MC open circuit current recirculating path is implemented in the fault detection method to avoid false diagnosis. The proposed idea is investigated using SYNOPSYS SABER. simulation results and experimental results are presented to validate the ideas and implementation.

II. Matrix Converter Open Circuit Fault Behavior Analysis

Matrix converters provided no free-wheeling mechanism, so a clamp circuit is needed to protect the matrix converters from over-voltage during open-circuit fault conditions as shown in

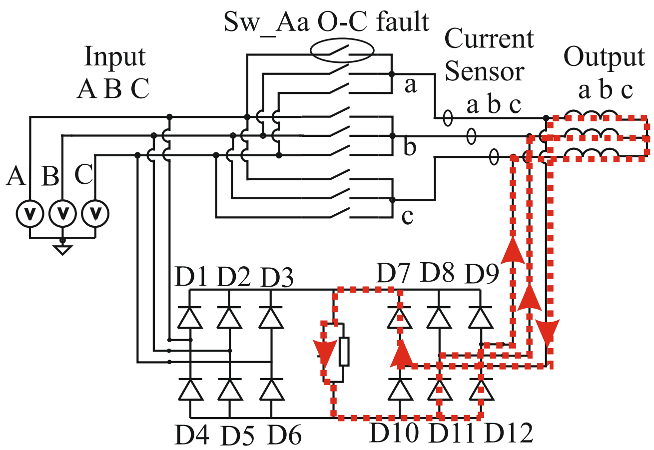


Fig. 1: Type 1 path

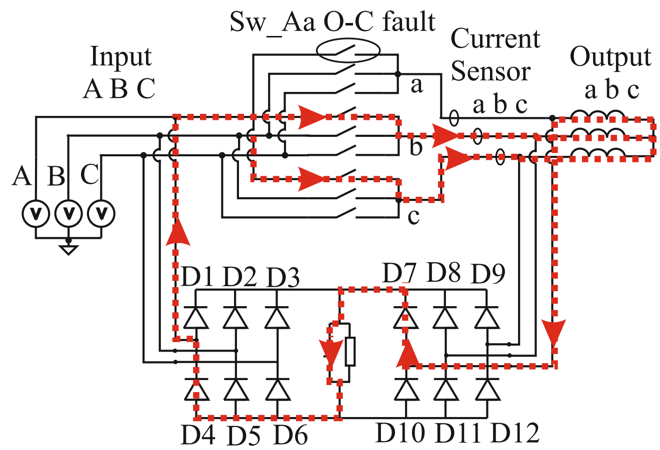


Fig. 2: Type 2 path

Fig 1 and 2. Normally, the matrix converter input terminals should not be short circuited because it is fed by a voltage source. On the other hand, an output phase of a matrix converter must never be open circuited due to inductive load nature. Hence, the switching duty cycle of the matrix converter must satisfy the condition expressed in equation 1. Variables m_{hk} are the duty cycles of nine bidirectional switches Sw_{hk} in the matrix converter. The variable h represents the input side and k represents the output side.

$$\begin{aligned} 0 \leq m_{hk} \leq 1,\ h = A, B, C,\ k = a, b, c. \\ m_{Aa} + m_{Ba} + m_{Ca} = 1 \\ m_{Ab} + m_{Bb} + m_{Cb} = 1 \\ m_{Ac} + m_{Bc} + m_{Cc} = 1 \end{aligned} \tag{1}$$

When a bidirectional power switch is open circuited, the faulty MC output phase current will recirculate through the clamp circuit. There are two types of current recirculating paths of a direct matrix converter during an open circuit fault [14]. When the open-circuited output phase current is the biggest absolute value, type 1 current recirculating path will occur, which will cause the other two current sensors in the healthy output phase to measure a zero current. If the open-circuited output phase current is not the biggest absolute value, type 2 current recirculating path will occur and the other two current sensors will not measure a zero current. The type of current recirculating path is determined by the switch state, the input voltage as well as the output current direction. The healthy MC output phase currents will be influenced by the current recirculating through the clamp circuit as shown in Fig 1 and 2.

III. Proposed Fault detection Technique

Three output current sensors are located ahead of the output port of the clamp circuit, which means the three output current sensors will directly measure the matrix converter output current rather than load current. An asynchronous SVM arrangement using one zero vector is used to modulated the converter.The switch pattern is listed in the TABLE I. This method was used in order to maximize the length of the zero vector and increase the operating range of reliable fault detection since in practice, it is difficult to obtain clean current samples during small converter pulses. The switching pattern table shows each MC output phase should connect to which input phase respectively in each sector combination. The output current will be sampled within each of the four active vectors as well as within the zero vector. The current sampling points for fault detection and diagnosis purpose is presented in figure 3.

When bidirectional switch Sw_{Aa} occurs open circuit fault, the faulty switch will remain off when a switch-on signal is sent to the faulty switch through the gate drive circuit. The output current sensor a could detect the zero current in the fist applied vector which uses this faulty switch. For instance, if in input sector 1 and output sector 1 combination, all these five applied vectors will use the faulty switch. So the current sensor a will keep detecting the zero current within these five sampling points. When switch Sw_{Ba} or Sw_{Ca} occurs open circuit fault in input sector 1 and output sector 1 combination, even though the faulty switch cannot be located in this sector combination, the matrix converter will remain working normally because the faulty switch is not applied during the entire modulation period. If switch Sw_{Ac} occurs open circuit fault in input sector 1 and output sector 1 combination, and

TABLE I: Modified Space Vector Switch state table

$MC\ Output$	$Output_1$	$Output_2$	$Output_3$	$Output_4$	$Output_5$	$Output_6$
	$-3\ A\ C\ C$	$-6\ C\ A\ C$	$-6\ C\ A\ C$	$-9\ C\ C\ A$	$-9\ C\ C\ A$	$-3\ A\ C\ C$
	$+9\ A\ A\ C$	$+9\ A\ A\ C$	$+3\ C\ A\ A$	$+3\ C\ A\ A$	$+6\ A\ C\ A$	$+6\ A\ C\ A$
$Input_1$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$
	$-7\ A\ A\ B$	$-7\ A\ A\ B$	$-1\ B\ A\ A$	$+7\ B\ B\ A$	$+7\ B\ B\ A$	$+1\ A\ B\ B$
	$+1\ A\ B\ B$	$+4\ B\ A\ B$	$+4\ B\ A\ B$	$-1\ B\ A\ A$	$-4\ A\ B\ A$	$-4\ A\ B\ A$
	$-8\ B\ B\ C$	$-8\ B\ B\ C$	$-2\ C\ B\ B$	$-2\ C\ B\ B$	$-5\ B\ C\ B$	$-5\ B\ C\ B$
	$+2\ B\ C\ C$	$+5\ C\ B\ C$	$+5\ C\ B\ C$	$+8\ C\ C\ B$	$+8\ C\ C\ B$	$+2\ B\ C\ C$
$Input_2$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$
	$-3\ A\ C\ C$	$-6\ C\ A\ C$	$-6\ C\ A\ C$	$-9\ C\ C\ A$	$-9\ C\ C\ A$	$-3\ A\ C\ C$
	$+9\ A\ A\ C$	$+9\ A\ A\ C$	$+3\ C\ A\ A$	$+3\ C\ A\ A$	$+6\ A\ C\ A$	$+6\ A\ C\ A$
	$-1\ B\ A\ A$	$-4\ A\ B\ A$	$-4\ A\ B\ A$	$-7\ A\ A\ B$	$-7\ A\ A\ B$	$-1\ B\ A\ A$
	$+7\ B\ B\ A$	$+7\ B\ B\ A$	$+1\ A\ B\ B$	$+1\ A\ B\ B$	$+4\ B\ A\ B$	$+4\ B\ A\ B$
$Input_3$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$
	$-8\ B\ B\ C$	$-8\ B\ B\ C$	$-2\ C\ B\ B$	$-2\ C\ B\ B$	$-5\ B\ C\ B$	$-5\ B\ C\ B$
	$+2\ B\ C\ C$	$+5\ C\ B\ C$	$+5\ C\ B\ C$	$+8\ C\ C\ B$	$+8\ C\ C\ B$	$+2\ B\ C\ C$
	$-9\ C\ C\ A$	$-9\ C\ C\ A$	$-3\ A\ C\ C$	$-3\ A\ C\ C$	$-6\ C\ A\ C$	$-6\ C\ A\ C$
	$+3\ C\ A\ A$	$+6\ A\ C\ A$	$+6\ A\ C\ A$	$+9\ A\ A\ C$	$+9\ A\ A\ C$	$+3\ C\ A\ A$
$Input_4$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$	$0_A\ A\ A\ A$
	$-1\ B\ A\ A$	$-4\ A\ B\ A$	$-4\ A\ B\ A$	$-7\ A\ A\ B$	$-7\ A\ A\ B$	$-1\ B\ A\ A$
	$+7\ B\ B\ A$	$+7\ B\ B\ A$	$+1\ A\ B\ B$	$+1\ A\ B\ B$	$+4\ B\ A\ B$	$+4\ B\ A\ B$
	$-2\ C\ B\ B$	$-5\ B\ C\ B$	$-5\ B\ C\ B$	$-8\ B\ B\ C$	$-8\ B\ B\ C$	$-2\ C\ B\ B$
	$+8\ C\ C\ B$	$+8\ C\ C\ B$	$+2\ B\ C\ C$	$+2\ B\ C\ C$	$+5\ C\ B\ C$	$+5\ C\ B\ C$
$Input_5$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$	$0_C\ C\ C\ C$
	$-9\ C\ C\ A$	$-9\ C\ C\ A$	$-3\ A\ C\ C$	$-3\ A\ C\ C$	$-6\ C\ A\ C$	$-6\ C\ A\ C$
	$+3\ C\ A\ A$	$+6\ A\ C\ A$	$+6\ A\ C\ A$	$+9\ A\ A\ C$	$+9\ A\ A\ C$	$+3\ C\ A\ A$
	$-7\ A\ A\ B$	$-7\ A\ A\ B$	$-1\ B\ A\ A$	$-1\ B\ A\ A$	$-4\ A\ B\ A$	$-4\ A\ B\ A$
	$+1\ A\ B\ B$	$+4\ B\ A\ B$	$+4\ B\ A\ B$	$+7\ B\ B\ A$	$+7\ B\ B\ A$	$+1\ A\ B\ B$
$Input_6$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$	$0_B\ B\ B\ B$
	$-2\ C\ B\ B$	$-5\ B\ C\ B$	$-5\ B\ C\ B$	$-8\ B\ B\ C$	$-8\ B\ B\ C$	$-2\ C\ B\ B$
	$+8\ C\ C\ B$	$+8\ C\ C\ B$	$+2\ B\ C\ C$	$+2\ B\ C\ C$	$+5\ C\ B\ C$	$+5\ C\ B\ C$

also assuming the 0.866 modulation ratio with a extremely small zero vector period, this open circuit fault will not affect the performance of matrix converter because of its extremely small applying time period. Therefore, the proposed fault detection and diagnosis method will perform very well during high modulation ratio occasion.

IV. Expert Knowledge to Avoid False Diagnosis

In literature [14], the matrix converter current recirculation path analysis under open circuit fault condition shows that the healthy MC output phase current could be canceled to zero by the current recirculation through the clamp circuit. This expert knowledge is essential for current-signal-based and current sensor ahead-located fault location strategies to avoid false diagnosis. In order to acquire the correct diagnosis results, four types of information are needed listed below:

a). Matrix converter output current amplitude and direction information for previous modulation period.

b). Matrix converter output current amplitude and direction information for present modulation period.

c). Matrix converter switch states for present modulation period.

d). Matrix converter input source voltage for present modulation period.

These four types of information will be acquired by the fault detection and diagnosis processor which will be implemented on the DSP-FPGA control board. The detail of diagnosis information acquirement is presented in figure 3. Type a information provides the matrix converter output currents state before a open circuit fault occurs, which will determine the current recirculating path through the clamp circuit.[14]. Once the current recirculating path is confirmed, the false diagnosis will be avoided successfully. The proposed fault detection and diagnosis method require no load model and can locate the

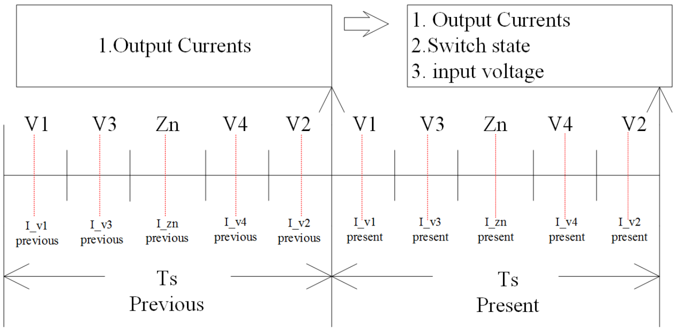


Fig. 3: Diagnosis information acquirement process

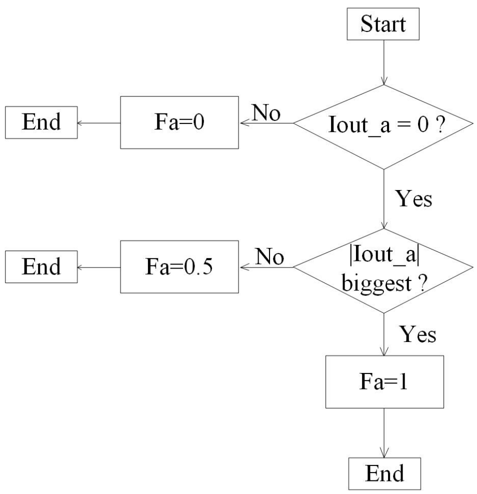


Fig. 4: Fault detection flow chart for phase a

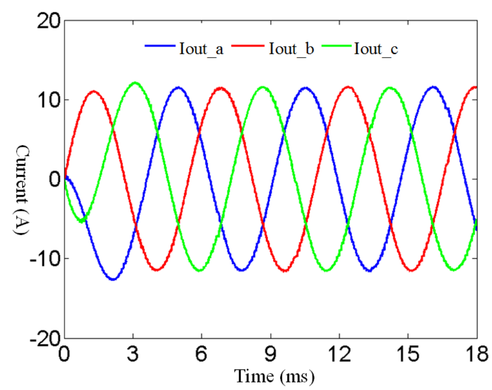
faulty switch within two modulation periods.

When an open-circuit fault occurs, the proposed fault detection method will first identify the faulty output phase of the matrix converter. If the output current is detected as 0, the respective output phase should be identified as open-circuited faulty phase. The corresponding flag of F_a, F_b, F_c will be set to 1 or 0.5 to show the possibility of the faulty phase. Then the faulty switch of the matrix converter can be identified by using switching states information as shown in equation 2. Since this paper focuses on single switch open-circuited fault, The switch which has the highest possibility will be identified as a faulty switch. The proposed fault detection method is presented in Fig 4.

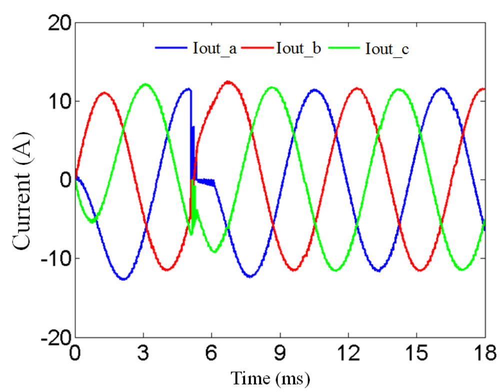
$$\begin{bmatrix} F_{Aa} & F_{Ba} & F_{Ca} \\ F_{Ab} & F_{Bb} & F_{Cb} \\ F_{Ac} & F_{Bc} & F_{Cc} \end{bmatrix} = \begin{bmatrix} F_a & 0 & 0 \\ 0 & F_b & 0 \\ 0 & 0 & F_c \end{bmatrix} \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \tag{2}$$

V. Simulation Results

Simulation results are obtained for all 36 input-output sector combinations when bidirectional switch Sw_{Aa} occurs open circuit fault. Simulation results of sector combination $Input_1$ and $Output_5$ are presented to validate the proposed fault detection and diagnosis method. Firstly, matrix converter output current waveforms under both normal operation and open circuit fault conditions are presented in figure 5. Then, the magnified waveforms of switch states, faulty currents, and input voltages are presented in figure 6. A fault detector is designed to verify the validity of the proposed fault detection technique. The faulty output current waveform and the fault diagnosis flag waveform is shown in figure 7. It can be seen from the result that healthy output $phase_b$ will not be diagnosed as open circuit fault when applying the proposed fault detection technique.



(a) Output current under normal operation condition



(b) Output current under open circuit fault condition

Fig. 5: Matrix converter diagnosis process and output currents under both normal and open-circuit fault operation

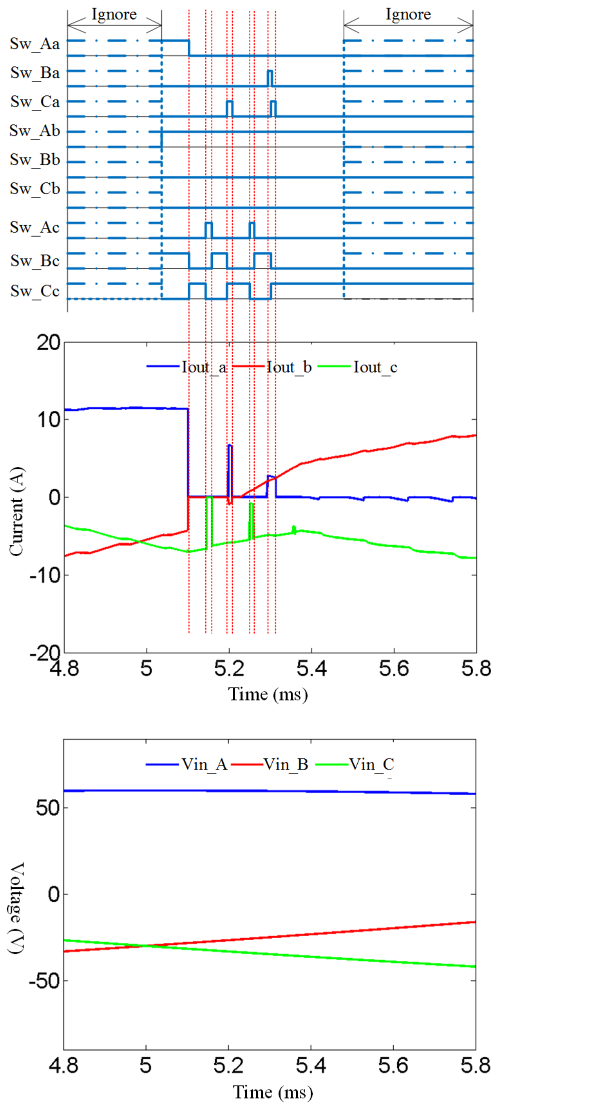


Fig. 6: Matrix converter switch state, output current and input voltage waveform under open circuit fault condition

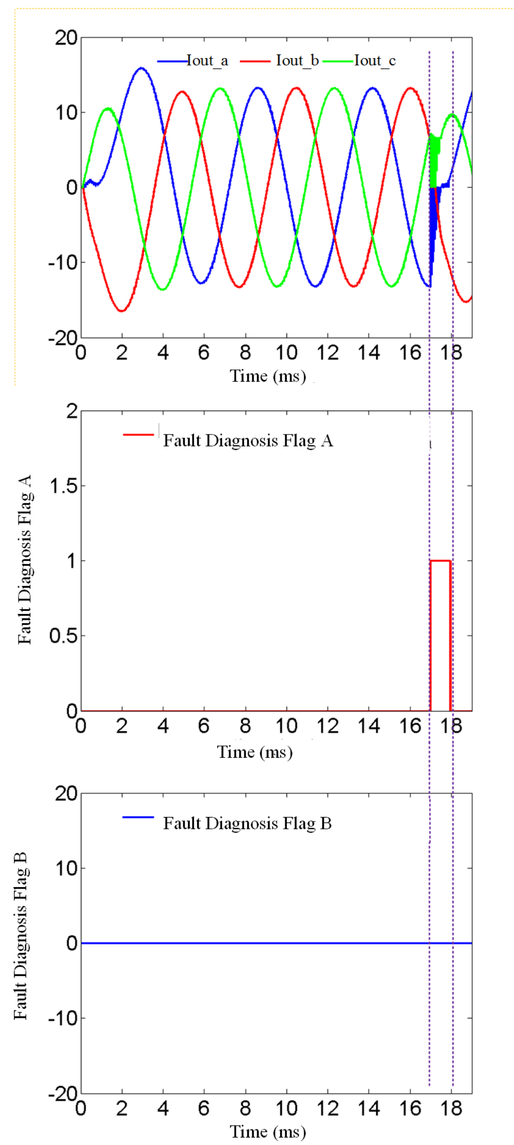


Fig. 7: Matrix converter fault detection and diagnosis result

VI. Conclusion

This paper has presented a fault detection and diagnosis method for matrix converters with expert knowledge built in to avoid false diagnosis. The fault detection and diagnosis processor needs output currents, input voltages, and switch state information together to make a correct fault diagnosis result. This novel method requires no load model and can locate the fault within two modulation periods.

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