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Open Circuit Fault Detection and Diagnosis in Matrix Converters

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Abstract—With the increased use of power electronics in aerospace, automotive, industrial, and energy generation sectors, the demand for highly reliable and power dense solutions has increased. Matrix converters become attractive when taking into account demands for high reliability and high power density. With their lack of large bulky DC-link capacitors, high power densities are possible with the capability to operate with high ambient temperatures. When a power converter needs high reliability, under tight weight and volume constraints, it is often not possible to have an entirely redundant system. Taking into account these constraints it is desirable that the power converter continue to operate even under faulty conditions, albeit with diminished performance in some regard. This paper presents an open circuit switch fault detection and diagnosis system for matrix converters, which has been experimentally validated. The presented system requires no load models, averaging windows or additional sensors, this makes the proposed method fast and low cost.

Keywords—AC-AC power conversion, Fault diagnosis.

I. INTRODUCTION

WITH the increased uptake in power electronic drives and power supplies in the manufacturing, power generation, rail, automotive and aerospace industries there has been an increase in demand for highly reliable and power dense power electronic solutions. For example the expected life of a photovoltaic installation is around twenty years, but a typical grid connected power converter has an operational lifetime of only five years [1][2]. In such situations it is almost inevitable that at some point during the system lifetime, a fault will occur in the power electronics. In those cases where it is not possible for the faulty converter to be fully redundant, it is still desirable for the converter to continue to operate. Often systems will allow continued operation during a fault with less than optimal performance [3]. Continued operation of the equipment under faulty conditions can be a desirable feature for mission critical systems, such as surface actuation systems on aircraft or braking systems in automobiles [4].

The focus for this paper is fault detection and diagnosis in direct AC-AC matrix converters. Traditionally, the converter topology used for AC-AC conversion is a back-to-back configuration of a rectifier and inverter. Both the rectifier and inverter are based on a three phase bridge circuit, making them simple to control. Modern motor drives tend to use a back-to-back configuration because it is a mature technology which is well understood. The main problem with inverter based drives in AC-AC fault tolerant applications is that in a back-to-back configuration, a DC-link is required, which is a single point

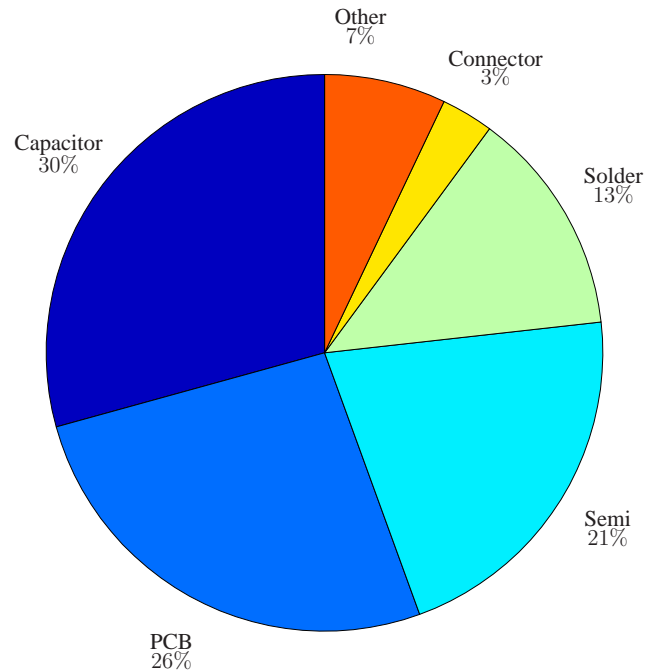


Fig. 1. Failure Distribution in Power Electronics [5]

of failure; in a voltage source back-to-back configuration a DC-link capacitor is required. The converter failures caused by capacitor faults account for 30% of total converter failures [5] as shown in Fig. 1. Where as semiconductor faults are responsible for only 21% of failures [5]. Matrix converters do not have DC-Links and do not suffer from the single point of failure which afflicts the back-to-back configuration[6][7][8]. This feature makes the matrix converter an attractive power converter for use in fault tolerant systems.

A comparison of the relative Mean Time Between Failure (MTBF) of various AC-AC power converters is shown in Table. I [9]. The meaning of MTBF is often misunderstood, MTBF is not the time taken for a single unit to fail, it is the total failures divided by total operating population time [10]. If a power converter had a MTBF of 1000 hours and 1000 units were in operation, then on average one would fail every hour [10]. In terms of MTBF the matrix converter is not quite as reliable as a 6 pulse rectifier-inverter back-to-back configuration as shown in Table. I, this is because the matrix converter has more controlled switches and thus more gate

drives [9]. When compared to an 18 pulse or PWM rectifier back-to-back configuration the matrix converter is actually more reliable, in terms of MTBF [9][11]. This is because the switches in the matrix converter topology have less voltage stress than those in the PWM rectifier-inverter drive [9][11].

Topology	Failure Rate (λ) Failures per Hour	Mean Time To Failure ($1/\lambda$) Hours to Failure
Rectifier(6 Pulse) Inverter	26.0610^{-6}	37592
Rectifier(12 Pulse) Inverter	29.0210^{-6}	34464
Rectifier(18 Pulse) Inverter	30.7210^{-6}	32550
Rectifier(PWM) Inverter	31.0910^{-6}	32166
Matrix Converter	28.6610^{-6}	34894

TABLE I. COMPARISON OF AC-AC MOTOR DRIVE RELIABILITY [9]

The switches that make up a matrix converter can either fail open circuit or short circuit, this work focuses on open circuit switch faults. Common causes of open circuit switch faults include gate drive faults, wire bond lift-off and cracking of solder layers [12][13]. Research has been carried out on the continued operation of a matrix converters during an open-circuit switch failure [14][15]. These methods require a fault detection and diagnosis method that is both fast and reliable. There are several existing methods in the literature for detecting open circuit switch faults in AC-AC converters. One method for open circuit fault detection in AC-AC converters is the error voltage method, in these methods the node voltages of an inverter [16][17] or matrix converter [18] are compared to a set of reference voltages. The differences between the estimated and actual voltages are then used for fault detection and diagnosis. The problem with the output voltage methods is that the voltages sensors are not normally required for operation of the converter. These methods add to the cost and reduce the reliability of the converter. Spectral methods have also been applied to matrix converters but these methods cannot diagnose the faulty device in direct matrix converters [19][20]. Another method uses a low frequency estimate of the output current of the converter and compares this to the actual output current of the AC-AC converter [21][22]. These low frequency methods use the existing output current sensors and do not alter the cost or reliability of the converter. These methods do not detect the fault when it poses the largest risk to the converter; when the output current is close to the nominal value. This is because at this point the error signal used in the low frequency methods is zero or close to zero. Another drawback of the low frequency methods is that they require a load model, to estimate the output currents. If the load is not well defined then this requirement can decrease the performance of the low frequency methods.

This paper presents a fault detection and diagnosis method which is fast, reliable, requires no additional hardware, detects and diagnoses the faulty device while it poses the largest risk to the converter and requires no load model. The presented method has been experimentally validated using an custom built matrix converter rated at $10kVA$.

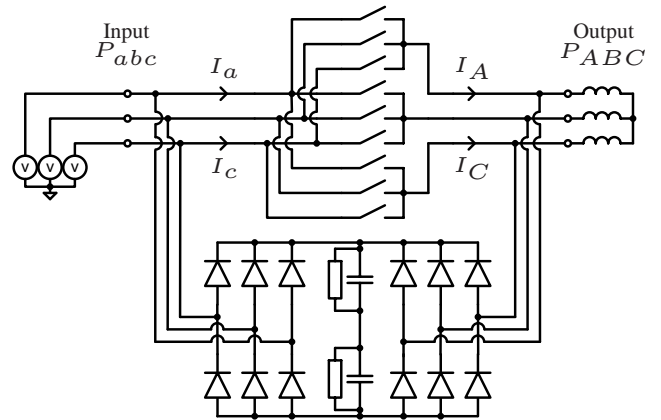


Fig. 2. Circuit Diagram of the Matrix Converter with the Clamp Circuit

II. MATRIX CONVERTER OPERATION DURING AN OPEN CIRCUIT SWITCH FAULT

The matrix converter control requires accurate information in order to safely commutate the inductive load current between the input voltage sources. Either an input voltage direction commutation method [23] or an output current direction commutation method is needed [24]. These two methods behave differently during a commutation where the input voltage or output current direction information is incorrect, the input voltage method creates a short circuit between the input voltage sources and the output current method creates an open circuit of an output current source [25]. When using either commutation method a protection circuit is required to prevent dangerous over voltage during a load open circuit [26]. Most matrix converters with a kVA rating above $2kVA$ use a clamp circuit as the over voltage protection circuit [27][28]. This clamp circuit operates by providing a current path for the load current during an open circuit fault, thus preventing dangerous over voltages. Matrix converters rated under $2kVA$ can be protected using other energy absorbing devices such as varistors [29]. In the presented work the converter is protected from over voltage by a voltage clamp circuit and four step output current commutation was chosen so that during an incorrect commutation sequence the converter is protected by the voltage clamp circuit.

The clamp circuit is connected in parallel with the matrix converter, as shown in Fig. 2. The port connected to the voltage sources will be referred to, as the input port and called P_{abc} . The port connected to inductive load will be referred to, as the output port and called P_{ABC} .

During an open circuit switch fault, the load current flows through both the matrix converter and clamp circuit. In the following example an open circuit is introduced on output phase A. This can cause current to be conducted both in a recirculating manor through the output diodes of the clamp circuit, see Fig. 3. Another current path exists through the input diodes of the clamp circuit, through the matrix converter and finally returning to the load see Fig. 4. A final current path exists through one of the input voltage sources, through the matrix converter then returning to the load, see Fig. 5. In all

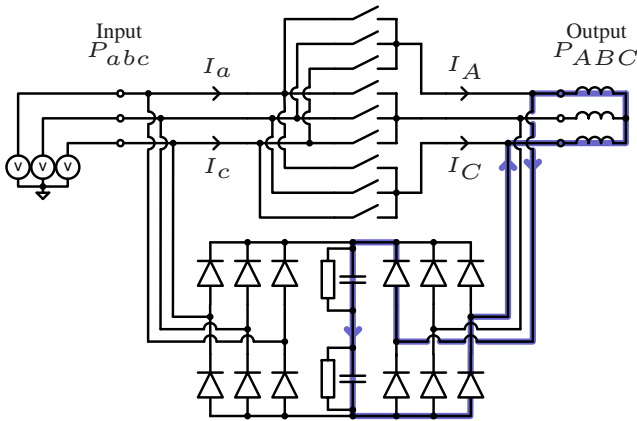


Fig. 3. Circuit Diagram of the Matrix Converter and Clamp Circuit, With Possible Current Path One Highlighted

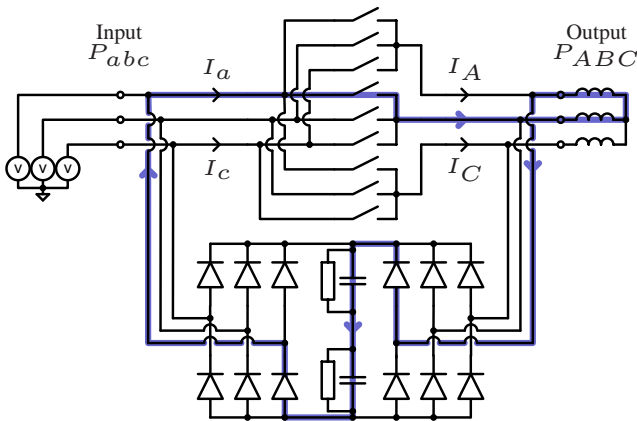


Fig. 4. Circuit Diagram of the Matrix Converter and Clamp Circuit, With Possible Current Path Two Highlighted

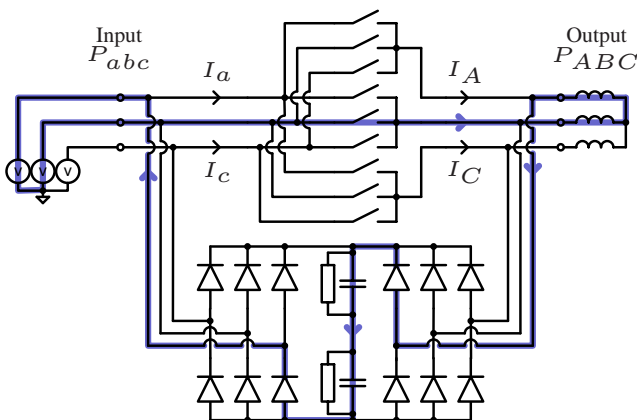


Fig. 5. Circuit Diagram of the Matrix Converter and Clamp Circuit, With Possible Current Path Three Highlighted

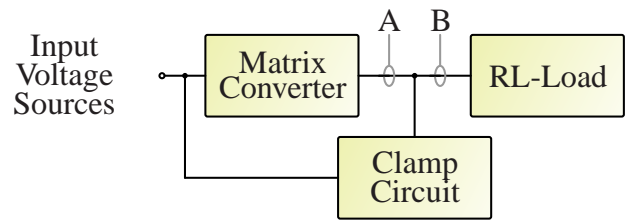


Fig. 6. Block Diagram Showing Two Possible Matrix Converter Current Sensor Locations

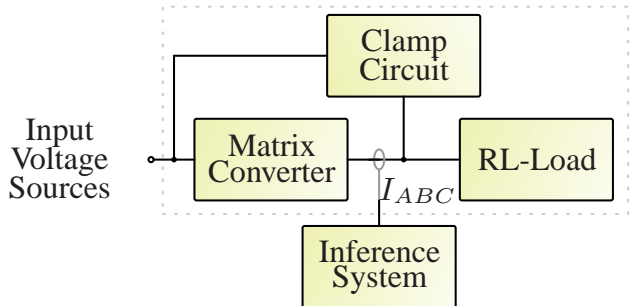


Fig. 7. Block Diagram of the Proposed Fault Detection and Diagnosis System

cases there is zero current flow through the faulty output phase of the matrix converter during the fault. The method presented in this paper uses this knowledge together with information on which devices are gated to detect the open circuit switch fault.

III. PROPOSED DETECTION TECHNIQUE

Traditionally the load currents of the matrix converter are measured for control purposes [30], as shown in Fig. 6(case B). In this case the measured current is both the clamp current and matrix converter current. In the proposed method the current sensors are moved ahead of the clamp circuit connection, as shown in Fig. 6(case A). In this case only the current flowing through the matrix converter is measured. During normal operation the current measured in both cases A and B will be the same, meaning that the plant used for controller design remains unchanged. However, during an open circuit switch fault, the current measured in case A would be zero, as the current flows through the clamp circuit instead. This change in the current path can be used to accurately detect an open circuit switch fault. This, together with information about the switch state of the matrix converter is required in order to diagnose which bidirectional switch is faulty. It should be noted that the new current sensor location does not adversely effect traditional over current protection as the converter current is measured directly. To elaborate a short circuit on the load port causes no over voltage. So the voltage clamp circuit will not conduct, meaning all of the current must flow through the bidirectional switches and the current sensors.

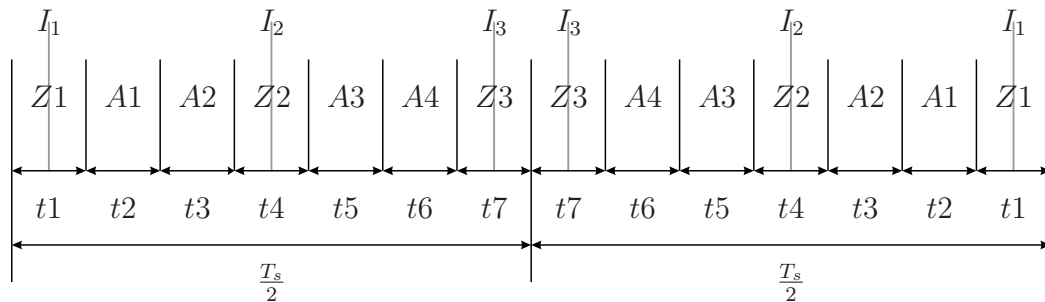


Fig. 8. Graphical Representation of a Symmetrical Switching Pattern for Space Vector Modulation

The experimental converter used Space Vector Modulation (SVM) as described in [31]. In this modulation scheme four active-vectors are used and three zero-vectors are used per modulation period. During the zero-vectors, all of the output phases should be connected to the same input phase by the matrix converter; however during an open circuit fault one output phase will be left open. If the converter currents are sampled during the zero-vectors then the switch state of the matrix converter is known. With knowledge about the switch state along with the current sensor location, fast and accurate fault detection and diagnosis of open circuit switch faults can be performed. In the experimental converter implementation, a symmetrical modulation pattern was used and is shown in Fig. 8, here T_S is the modulation period. Using this modulation pattern each of the zero-vectors Z1, Z2 and Z3 are used twice per modulation period. The six sample points I_{123} are also shown. This means that during any modulation period all of the bidirectional switches of the matrix converter are used at least twice. So a fault can be detected within $T_S/2$ of its occurrence. Since all of the output phases behave in the same manner during the zero-vectors, a detection and diagnosis scheme developed for a single output phase can be applied to all output phases of the converter.

A. Implementation Details

A simplified block diagram of the detection scheme is shown in Fig. 7, the detection scheme uses the measured matrix converter output currents (I_{ABC}) for fault detection and diagnosis. The detection and diagnosis system uses expert knowledge about the converter current path during a fault together with the expert knowledge about the switch state of the converter during the zero-vectors. In the proposed implementation the output currents are sampled once during each of the six zero-vectors that are present in the symmetrical SVM modulation pattern, see Fig. 8. Where I_{123} are the sample points for the matrix converter output currents. To ease analysis only three samples will be used because the other three samples are identical.

Information is taken directly from the modulator of the matrix converter and used to strategically sample the output currents during a modulation period. These samples are then used to detect and diagnose the fault by checking for differences in the currents flowing through the matrix converter

during the zero-vectors.

An idealised set of examples is shown in Fig. 9; only half of the modulation period is shown as the other half is symmetrical. The vertical dotted lines show the commutation points and the vertical solid lines represent the sample points. The three examples Fig. 9(b)-9(d) show idealised cases where the faulty device is only used in a single zero-vector and not in the active-vectors. If the currents are sampled at the solid lines the faulty device can be detected and diagnosed easily by taking the differences between the three samples and analysing the resulting residuals. The load current is always changing, but if the modulation frequency is high enough then the load current appears constant within one modulation period [32], so the difference between the output current samples should be zero. During a fault there is a difference between the output current samples so the fault is detected when the residuals are non-zero. Taking the difference between the output current samples taken during the same modulation period removes the load dependence from the proposed method. The faulty device can be diagnosed by using the knowledge about which output phase current contains the differences and the knowledge about the zero-vector in which the difference was detected gives insight about which bidirectional switch in that output phase is faulty. So if all three zero-vectors are used in each modulation period then the fault can be diagnosed within that modulation period, assuming the output current is non-zero.

This method is not ideal because during the natural zero crossing of the output current the difference between the output current samples will be zero. During the zero crossing the fault cannot be detected, because all of the residuals would be zero which is the same as in the healthy case. So the performance of the presented method will depend on the instantaneous magnitude of the output current.

IV. EXPERIMENTAL SETUP

This section describes the experimental matrix converter circuit along with its associated peripheral circuits. The matrix converter was rated at $10kVA$ and had a modulation frequency of $8kHz$. A block diagram of the developed matrix converter is shown in Fig. 10, which includes the switch matrix circuit and several peripheral circuits such as:

- Output Current Sensors
- Input Voltage Sensors

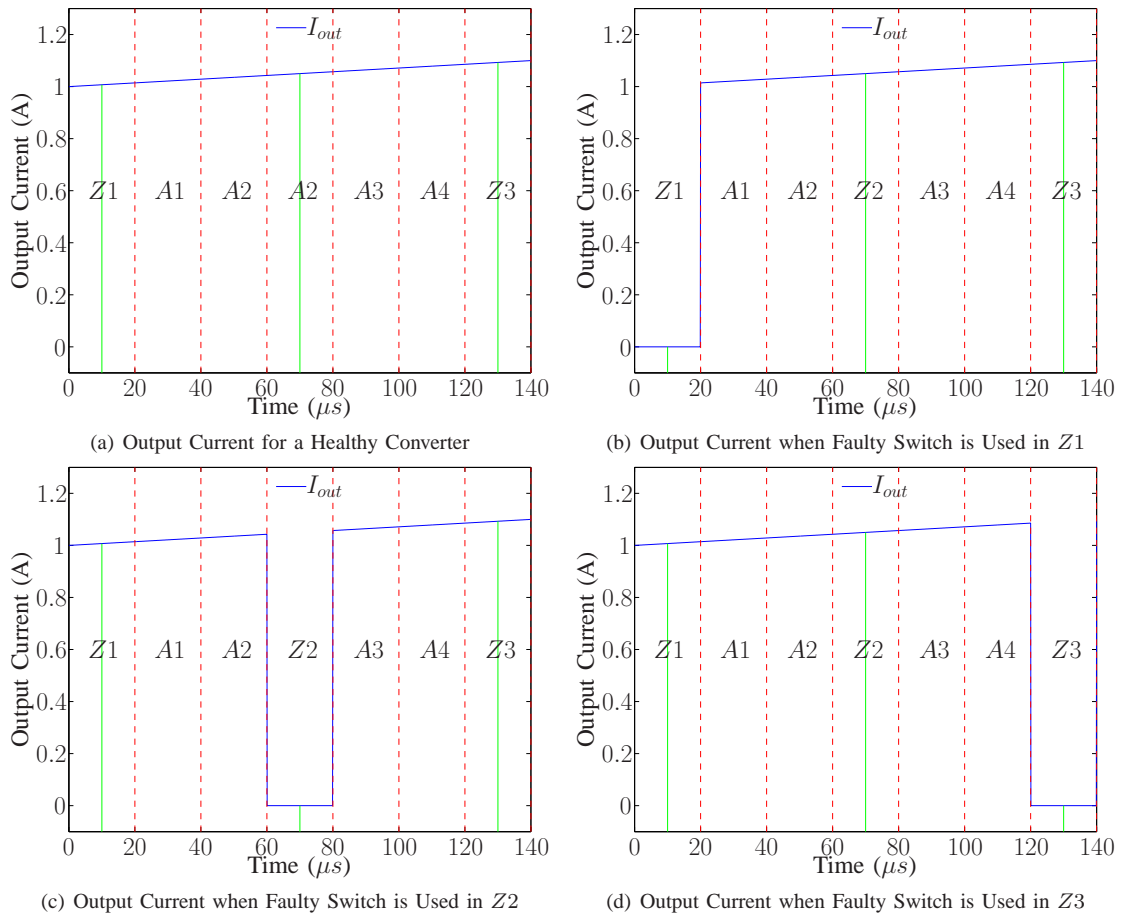


Fig. 9. Idealised Examples of a Single Matrix Converter Output Current During Open Circuit Switch Fault in Which the Faulty Device is Only Used in the zero-vectors

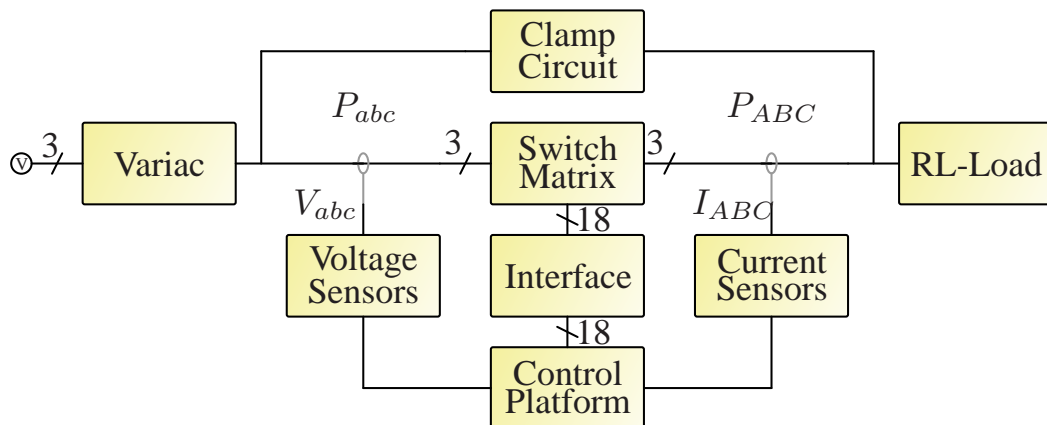


Fig. 10. Block Diagram of the Experimental Set-Up Used for Validation

- Control Platform
- Interface Card
- Clamp Circuit

To accommodate the intentional open circuits introduced during testing the clamp circuit was over-sized. The output connection of the clamp circuit was connected close to the inductive load and the connection for the current sensors were kept to a minimum distance to minimise the stray inductance of the connection. Current shunts were chosen as they offered the required analog bandwidth and offered a higher temperature operation than similar competing technologies. The current sensors were interfaced with the control platform which controlled the sampling process in real-time. A photo of the experimental setup used to validate the fault detection and diagnosis method is shown in Fig. 11, the photo shows the matrix converter power circuit, clamp circuit and current sensors.

One implementation issue of the proposed method is the use of an optimal switching pattern. When an optimal switching pattern is used, the order of the zero-vectors is changed depending upon the input - output sector combination [33]. The experimental converter used an optimal switching pattern but as the micro-controller implemented both the sampling system and the SVM, the order of the sampling points was reordered along with the optimal switch patterns. This ensured that the detection and diagnosis system is always given the output current samples in the correct order. The added complexity of scheduling and simultaneous sampling is minimal because most modern micro-controllers have integrated timer arrays which can be used to control the sampling points.

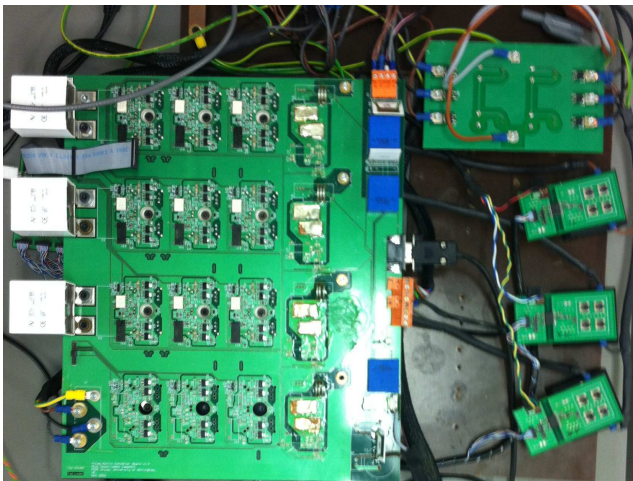


Fig. 11. Photograph of the Experimental Rig, On the left is the Matrix Converter Power Circuit, in the Upper Right is the Over-sized Clamp Circuit and on the Lower Right are the Three Current Sensors

V. RESULTS

The change in the load current during a modulation period is small, so the only disturbance in the converter output currents

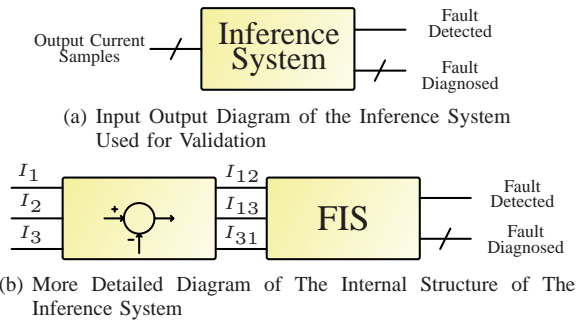


Fig. 12. Implementation of The Fault Detection System

within a modulation period is caused by an open-circuit switch fault. The presented method samples the output currents in each zero-vector and compares them to one another to detect and diagnose the fault. As symmetrical modulation is used there will be data duplication because each zero-vector is used twice. So only three samples are required for fault detection and diagnosis.

As mentioned previously, the current sampled in the zero-vector in which all of the output phases are connected to input phase *a* will be referred to as I_1 . A fault was introduced in each of the bidirectional switches in output phase A consecutively. The three converter current samples required for fault detection are shown in Fig. 13. The first plot Fig. 13(a), shows all three faults. The difference in the currents is hard to see at this scale. The remaining plots Fig. 13(b) - 13(d), show the same data but are magnified. Here the anticipated difference between the output current of the converter can be seen, from this initial inspection it is possible to detect and diagnose the fault manually. In the first case the current sample corresponding to the first zero-vector in the first output phase remains different from the other two samples so the faulty device is *swaA*, as this device is meant to be closed in this zero-vector. The limitations of this method are also clear from this first inspection, if the load current is zero then the difference between the currents in the faulty zero-vector and the healthy zero-vectors will also be zero. So detection and diagnosis will not be possible during this condition.

An input-output diagram of the inference system is shown in Fig. 12. The inference system shown in Fig. 12(b) could be an expert system, a neural network, a fuzzy inference system or any other system capable of making an informed decision. In this work a Fuzzy Inference System (FIS) was chosen. In the proposed method the inference system used the differences in the samples to evaluate whether there is an open circuit fault and if so which switch is likely to be open circuit. Taking the difference between the currents sampled during the same modulation period means that the operating point of the converter need not be taken into account by the inference system. The results of this inference system are shown in Fig. 14. An output value of 1 indicates that a fault is likely and a value of 0 indicates that a fault is unlikely. As anticipated the inference system cannot detect or diagnose the fault when the load current is zero as shown in Fig. 13(c). In this case the

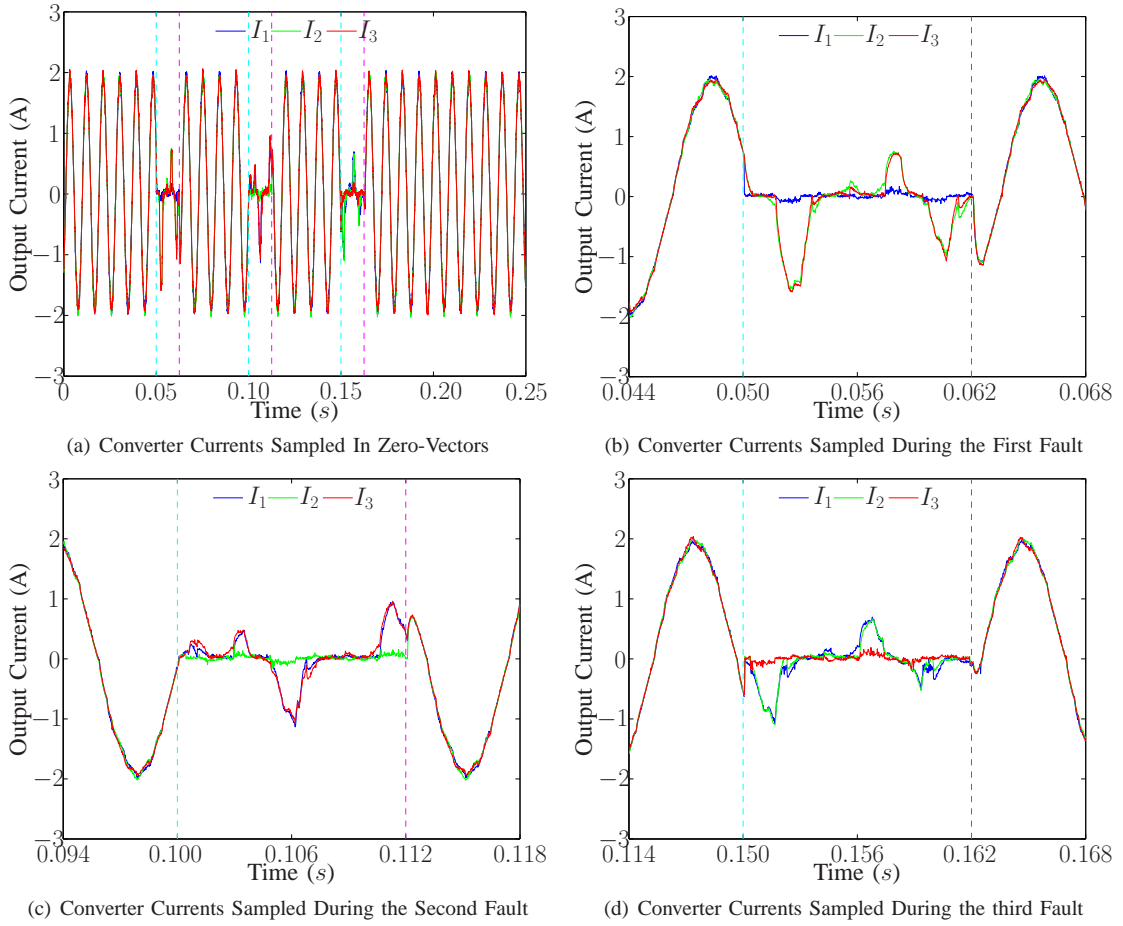


Fig. 13. Converter Currents Sampled in the Zero-Vectors During Three Subsequent Open Circuit Switch Faults

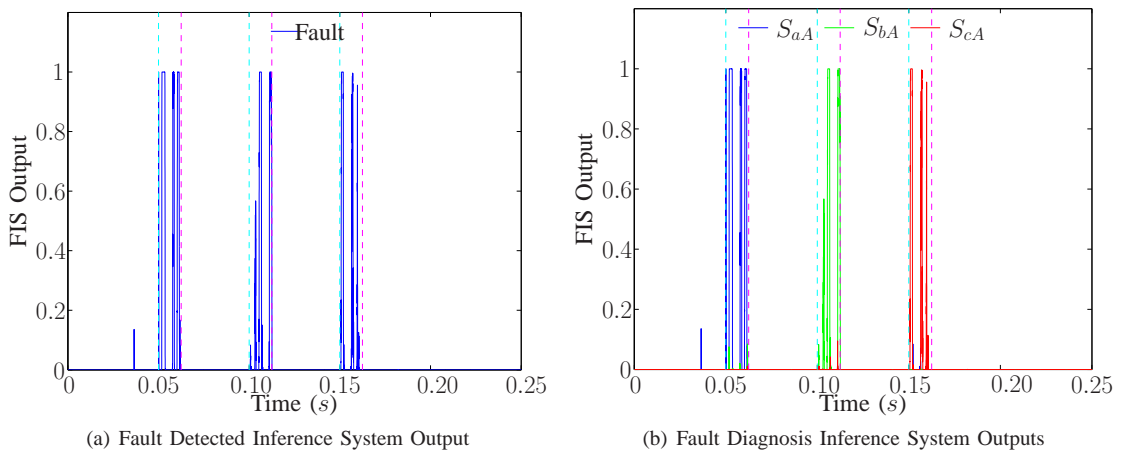


Fig. 14. Inference System Outputs During the Three Subsequent Open Circuit Switch Faults

fault was triggered during the natural zero crossing, this is the worst case scenario for the presented method. However when the load current is non-zero the proposed method performs well at both detecting and diagnosing the fault as shown in Fig. 14(a) and Fig. 14(b) respectively. It should be noted that the proposed methods does not false trigger.

The performance of this detection method will depend on the accuracy and immunity to noise of the current sensors. It should be noted that the currents shown here are unfiltered and taken directly from the converter current sensors. The operating point of the converter was quite low, with a peak value around 2A. This is important to note since with higher output current the performance of the method would be much better as the signal to noise ratio of the sensors would increase.

VI. CONCLUSION

This paper has presented a novel open circuit fault detection and diagnosis method for matrix converters. The method has been demonstrated experimentally. So long as the zero-vectors of the matrix converter are used in each modulation period the modulation scheme itself does not matter as no information about modulation is needed by the inference system. The fault detection method can be evaluated twice per modulation period when using SVM and a symmetrical modulation pattern. The method detects the open circuit switch fault when it poses the greatest risk to the other switches in the faulty phase, i.e. when the load current is non-zero. Future work should focus on the expansion of the proposed method for a N by M matrix converter.

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