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# A fault tolerant single sided matrix converter for flight control actuation systems*

Xiao-yan HUANG†1, Mao-jing JIN[2], Jian-cheng ZHANG[1], Qin-fen LU†‡1, You-tong FANG[1], Andrew GOODMAN[3], Chris GERADA[3]

([1]*College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China*)
([2]*High Technology Research and Development Center, Ministry of Science and Technology, Beijing 100044, China*)
([3]*University of Nottingham, Nottingham NG72RD, UK*)
†E-mail: {eezxh, luqinfen}@zju.edu.cn

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**Abstract:** We describe a single sided matrix converter (SSMC) designed for safety critical applications like flight control actuation systems. Dynamic simulations of multi-phase SSMC using Matlab Simulink are carried out to evaluate the fault tolerance capabilities. Investigation into different numbers of phases and power converter topologies under single phase open circuit, single switch open circuit, and single switch short circuit has been executed. The simulation results confirm 5-phase SSMC design as a compromise between fault tolerance and converter size/volume. A 5-phase SSMC prototype was built. Experimental results verify the effectiveness of our design.

**Key words:** Single sided matrix converter, Fault tolerance, Flight control actuation systems
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## 1 Introduction

In modern aircraft, thinner wings can be used for either improved aerodynamic efficiency or improved structural efficiency. This will, however, severely limit the installation space for flight control surface actuation systems. The limitation of space will make the current hydraulic actuator assemblies infeasible. Since the aircraft moves steadily towards the 'more electric aircraft' (MEA), the electrically powered actuation systems have been receiving intensive attention due to advantages in terms of reduced weight, compact structure, easier maintenance, increased safety, and enhanced reliability (Churn *et al*., 1998; Gerada and Bradley, 2008; Bennett *et al*., 2010; 2011; Vaseghi *et al*., 2011).

The proposed electrical actuation systems employ either an electro-hydrostatic actuation system (EHA) or an electrical mechanical actuation system (EMA). The performance of an electrical actuation system is determined mainly by the torque, speed, and power of its electrical drive. The foundation of the design is a compact system which could be fitted in the thinner and optimized wing with high reliability and fault tolerance capability. Therefore, the drive should be carefully designed to meet the demanding in reliability and performance criteria (Bennett *et al*., 2012). In safety critical applications, the fault tolerance and reliability of the whole electrical drive including the motor and power converter are of equally great importance. Thus, the main objective of this paper will be focused on the design of a 12 kV·A fault tolerant power converter for flap control of the Airbus

‡ Corresponding author
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340. The fault tolerant motor design has been discussed in Huang *et al*. (2012) and therefore is not included in this paper.

Recently, much research has been carried out on the development of fault tolerant voltage source inverters (VSIs) (de Araujo Ribeiro *et al*., 2004; Argile *et al*., 2008; Errabelli and Mutschler, 2012). Partitioning and redundancy are the simplest and most effective ways to achieve fault tolerance. Several three-phase fault tolerant VSI topologies with redundant power devices or units have been compared by Wechko (2004). The fault tolerance can be further enhanced by adopting a multi-phase design. Multi-phase VSI with high reliability and fault tolerance for aerospace applications has been proposed by several researchers (de Lillo *et al*., 2010; Villani *et al*., 2010; Shahbazi *et al*., 2012). Fault remedial strategies for inverter faults were reported by Bianchi *et al*. (2003).

However, for a conventional VSI, the energy storage device (electrolytic capacitor) can have a significant impact on the system reliability and is limited especially by its operating temperature range of −50–80 °C. Special, bulky DC link capacitors would have to be used. The failure of the DC link could stop the operation of the whole system. Therefore, in the flight control actuation system, this kind of critical component should be removed for higher reliability. Matrix converters were highlighted recently in aerospace applications due to the elimination of the bulky DC link capacitor and their potentially attractive features in terms of the unity power factor, regeneration capability, and simple and compact structure (Wheeler *et al*., 2002; Kwak and Toliyat, 2007; Khwan-on *et al*., 2012; Kwak, 2012). Comparison of the matrix converter and VSI has been reported by Aten *et al*. (2006).

A single sided matrix converter (SSMC) is the simplified matrix converter which keeps the advantages while avoiding the complex commutation problems of matrix converters (Goodman, 2007). In this paper, multi-phase SSMC is evaluated. The performances of multi-phase topologies under both normal and faulty conditions are analyzed and compared. Finally, a 5-phase prototype is built to verify the design.

## 2 Single sided matrix converters

The most common topology of the 3-phase VSI is shown in Fig. 1a. From the reliability point of view, the common power electronic components between phases may result in serious problems in case of a semiconductor failure. Thus, a modular topology like that in Fig. 1b has been proposed to improve reliability. However, the reliability is still reduced by the use of the energy storage component (the capacitor).

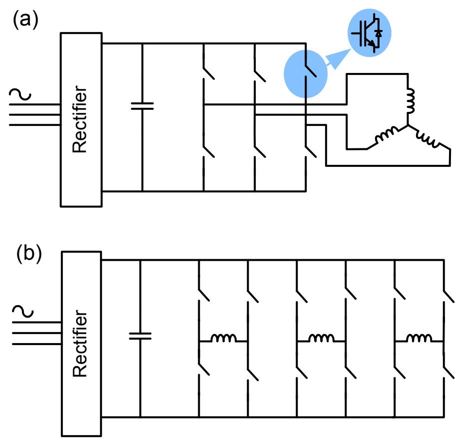


**Fig. 1 Topologies of a traditional 3-phase VSI (a) and a modular 3-phase VSI converter (b)**

### 2.1 Matrix converter

To eliminate the risk of failure of the critical components such as the energy storage component, the matrix converter concept is applied. In a matrix converter, bi-directional switches are used and controlled in such a way as to allow the converter to provide the high frequency output and regenerative power. A simplified block diagram of the typical 3-phase to 3-phase matrix converter is shown in Fig. 2. It consists of a matrix of nine bi-directional switches where each output phase can be connected to any input phase. The duty cycle of the switches is modulated to generate variable magnitude and variable frequency output.

The matrix converter has several advantages over the rectifier/inverter. The major advantage is the removal of the bulky energy storage component, which has a relatively short lifetime and cannot operate reliably in a high temperature environment. Another advantage is the bi-directional power flow. By appropriately controlling the switching devices, both the output voltage and input current can be made sinusoidal with harmonics at or above the switching frequency (Goodman, 2007).

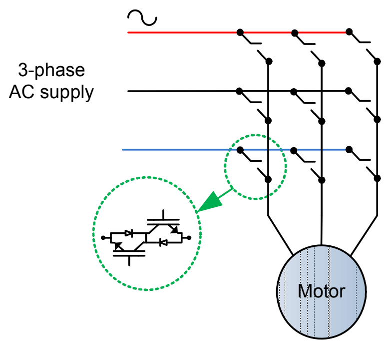


**Fig. 2 Topology of the 3-phase matrix converter**

Normally, however, a complex control procedure must be employed to obtain satisfactory performance. It requires a dedicated powerful micro-processor which needs to be officially approved. The use of such a micro-processor should be avoided for better reliability. A simple control strategy would be therefore preferred. Another disadvantage is that the output voltage is limited to 87% of the input voltage. This limitation can be overcome with certain techniques with the penalties of added complexity and deterioration in supply current waveform quality. Furthermore, it is particularly sensitive to the disturbances of the input voltage system.

## 2.2 Single sided matrix converter (SSMC)

An SSMC is a simplified matrix converter consisting of uni-directional switches instead of bi-directional ones (Fig. 3). Note that only the motors that can be driven using uni-directional load currents such as the switched reluctance motor and the brushless DC (BLDC) motor can be fed by the SSMC.

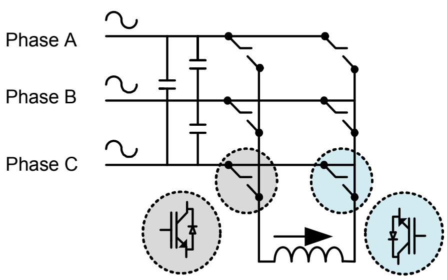


**Fig. 3 One unit of a single sided matrix converter**

A significant advantage is the elimination of the risk of creating a short circuit of the input phases during commutation. In the conventional matrix converter, an incorrectly timed commutation between phases would result in a short circuit between input phases to the converter, which would potentially destroy the insulated gate bipolar transistors (IGBTs) and disable the converter. However, the arrangement of IGBT and diode in the uni-directional switch cell means that the potential short circuit current will be blocked by the reverse biased diode. This means that the current commutation in an SSMC is far simpler and potentially more reliable than a standard bi-directional matrix converter. It is able to operate with higher power density and over a wider temperature range than conventional converters. The major converter disadvantages of the driving system are possible supply current distortion and the increased number of switches used compared to the commonly used pulse-width modulation (PWM) VSI. The SSMC rating is listed in Table 1.

**Table 1 Single sided matrix converter (SSMC) rating**

| Parameter | Value |
|---|---|
| Power | 12.5 kV·A |
| Nominal input voltage magnitude | 115 V |
| Variable input frequency | 360–800 Hz |

## 2.3 Double band hysteresis band control

Hysteresis (bang-bang) control is selected in this project for its simple operating principle, in which the current is controlled to be within a pre-defined band. The supply voltage needs to be identified as seven levels depending on its relative magnitude. These are defined as V+++, V++, V+, 0, V−, V−−, and V−−−, which represent the most positive to the most negative voltages. When the current exceeds the upper outer band, the most negative voltage (V−−−) will be applied. Otherwise, when the current is lower than the lower outer band, the most positive voltage (V+++) will be applied (Fig. 4). When the current is within the outer band but exceeds the inner band, the voltage will step up or down depending on the slope of the current. When the current is within the inner band, the supply voltage remains the same as the previous state.

The advantage of double band control is a much lower switching frequency and thus lower power loss for the power circuit. Another substantial advantage is the improved fault tolerance because seven voltage levels are available. This will be further explained in the following sections.

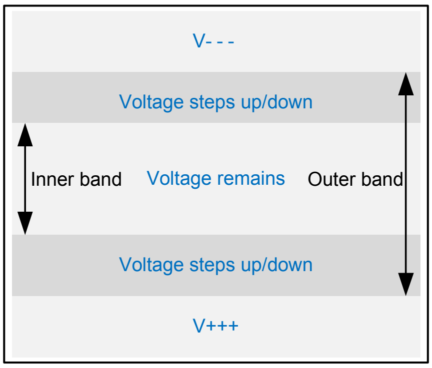


**Fig. 4 Double band control of single sided matrix converter (SSMC)**

## 3 Fault tolerance analyses

Fault tolerance is of great importance in aerospace applications especially when reliability and safety are two fundamental issues in the design. Thus, the fault tolerance capability of SSMC needs to be thoroughly investigated before the implementation. There are four main types of fault that may occur in power converters, including single phase open circuit, converter leg short circuit, single switch open circuit, and single switch short circuit.

Investigation into different numbers of phases and power converter topologies under four types of faulty condition has been executed. Details can be found in a previous conference publication (Huang *et al.*, 2007). The dynamic simulation was performed using the motor model derived from finite element method (FEM) software and the Simulink block in Matlab. The simulation results were compared and summarized in this paper.

### 3.1 Single phase open circuit (SPOC)

An SPOC condition is one of the most common faults that may occur in the drive system. For the modular $n$-phase VSI with bi-directional current supply, at any time, all the phases will be conducted. In the case of SPOC, no torque will be produced in the faulty phase while the other phases are not affected. The remaining average torque will be $1-1/n$ of the rated torque.

However, for the SSMC with uni-directional current supply, the flat top area of back-EMF (electomotive force) waveforms of the motor is about 140°. In this case, 120° and 90° uni-directional currents are supplied for 3- and 4-phase SSMCs, respectively, for lower torque ripples (Figs. 5a and 5b). Only one phase winding is conducted at any time for 3- and 4-phase drives. For 5- and 6-phase drives, 144° and 120° uni-directional currents are supplied, respectively, for better fault tolerance (Figs. 5c and 5d). In this case, at any time, two phase windings are conducted.

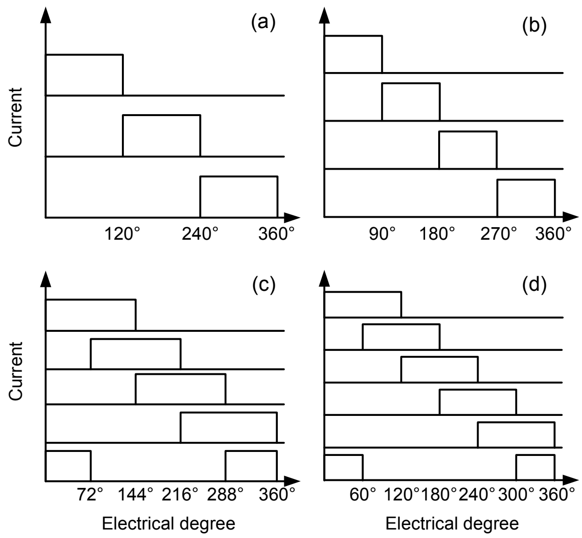


**Fig. 5 Current supply: (a) 3-phase; (b) 4-phase; (c) 5-phase; (d) 6-phase**

For the $n$-phase SSMC with one phase winding conducted at any time, losing one phase means no torque will be produced for $1/n$ of a period. The total remaining average torque will be $1-1/n$ of the rated torque, which means 66.67% and 75% average torque remaining for the 3- and 4-phase SSMCs, respectively. However, for the $n$-phase SSMC with two phase windings conducted at any time, losing one phase means half the torque will be produced for $1/n$ of a period. The total remaining average torque will be $1-1/(2n)$ of the rated torque, which means 90% and 91.67% average torque remaining for the 5- and 6-phase SSMCs, respectively.

The simulations of multi-phase SSMC with uni-directional motor current supply under single phase open circuit faults are carried out. For a 3- or 4-phase SSMC, it can be seen again that under this faulty condition no torque is produced for 1/3 or 1/4 of the period, respectively. For 5- and 6-phase converters, a minimum of half torque will still be available under the faulty condition. The periods of faulty operation are 2/5 and 2/6 of a cycle, respectively. The remaining average torques are 62%, 71%, 77%, and 81% of the rated torque for the 3-, 4-, 5-, and 6-phase drives, respectively (Fig. 6), which are all lower than the calculated value due to the existing torque ripples. However, it still proves: the larger the number of phases, the shorter the period of reduced torque operation, and thus the higher the average torque.

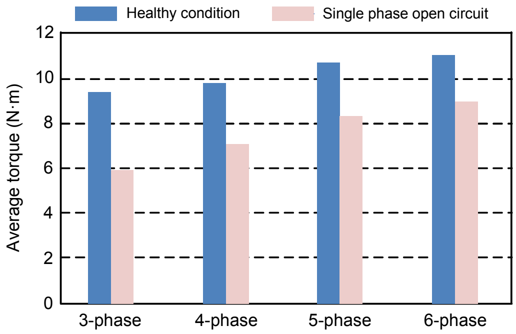


**Fig. 6 Average torques of the multi-phase single sided matrix converter (SSMC) drives under healthy and single phase open circuit conditions**

### 3.2 Single switch open circuit (SSOC)

Another common fault in the power converter is the failure of a single power device. For the traditional $n$-phase VSI, SSOC will have the same effect as SPOC. For the modular $n$-phase VSI, in case of SSOC, no torque will remain for half a period in the faulty phase. Therefore, the remaining average torque will be $1-1/(2n)$ of the rated torque, which means 83%, 87.5%, 90%, and 91.67% of the rated torque for the 3-, 4-, 5-, and 6-phase drives, respectively.

A merit of the SSMC is that the consequences of a rectifier component failure are reduced compared to the VSI. Furthermore, the torque ripple is smaller than that of the traditional converter under such a faulty condition. In the matrix converter, a single switch is connected to only one phase of the power supply, and if that IGBT fails to work, the other switches linking the other two phases of the power supply will continue to work. Therefore, 2/3 of full power capability in that phase is still maintained.

For the $n$-phase SSMC with one phase winding conducted at any time, losing one switch means no torque will be produced for $1/(3n)$ of a period. The total remaining average torque will be $1-1/(3n)$, which means 88.89% and 91.67% average torque remaining for the 3- and 4-phase SSMCs, respectively. However, for the $n$-phase SSMC with two-phase windings conducted at any time, losing one phase means half torque will be produced for $1/n$ of a period. The total remaining average torque will be $1-(1/2)(1/3)(1/n)$ of the rated torque, which means 96.67% and 97.22% average torque remaining for the 5- and 6-phase SSMCs, respectively.

Fig. 7 shows the torque and the faulty phase current waveforms of the 3-phase SSMCs with a faulty output phase. The current and torque waveforms for the 4-, 5-, and 6-phase SSMCs are similar, and thus are not presented here. More details can be found in Huang *et al.* (2007). When a single switch fails to work, the torque drops down to zero for a short while for the 3- and 4-phase SSMCs, but drops down to only half for a short while for 5- and 6-phase SSMCs. The more the power devices, the smaller the torque ripples will be (Fig. 8). The remaining average torques are 86%, 88%, 91%, and 93% of the rated torque for the 3-, 4-, 5-, and 6-phase SSMCs, respectively, which are all lower than the calculated value due to the existing torque ripples. However, it still proves that the larger is the number of phases, the higher is the average torque.

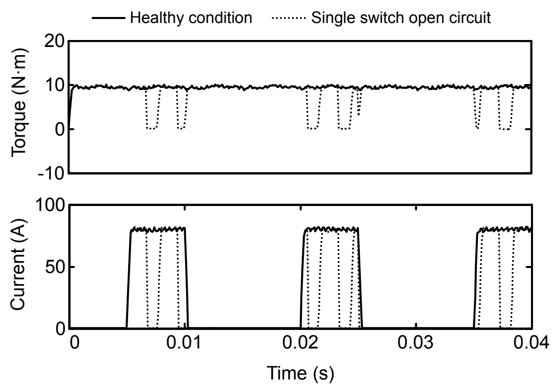


**Fig. 7 Output torque and current waveforms of 3-phase single sided matrix converter (SSMC) under healthy and single switch open circuit conditions**

Furthermore, the SSOC fault can be mitigated by using the double band hysteresis control. In double band control, there are seven voltage levels among which the applied phase voltage is selected at each change of the switching state. In the case of a single switch failure, a modification of the algorithm will just eliminate those voltage levels that are no longer available. Current conduction will remain continuous even though there has been a failure. The only consequence will be an increase in the switching frequency of the power devices under this version of hysteresis control.

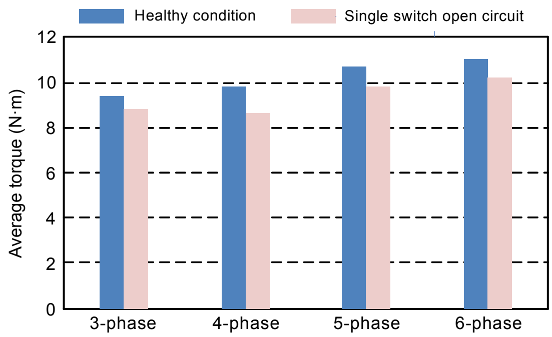


**Fig. 8 Average torques of the multi-phase single sided matrix converter (SSMC) drives under healthy and single switch open circuit conditions**

Obviously, SSMC requires more IGBTs than modular VSI. To make things worse, a multi-phase motor drive definitely requires more IGBTs than 3-phase systems. Table 2 shows the component requirements for different converters. The use of more power electronics switches appears to reduce the reliability of the drive. However, it is not always the case. The remaining average torque of the SSMC under SSOC is higher than that of the modular VSI.

**Table 2 Devices required for different types of converters**

| Converter | Number of devices required | | | |
|---|---|---|---|---|
| | IGBT | DS-IGBT | BC | DR |
| 3-phase VSI | 6 | 6 | 1 | 6 |
| 3-phase modular VSI | 12 | 12 | 1 | 6 |
| 3-phase SSMC | 18 | 18 | 0 | 0 |
| 4-phase VSI | 8 | 8 | 1 | 6 |
| 4-phase modular VSI | 16 | 16 | 1 | 6 |
| 4-phase SSMC | 24 | 24 | 0 | 0 |
| 5-phase VSI | 10 | 10 | 1 | 6 |
| 5-phase modular VSI | 20 | 20 | 1 | 6 |
| 5-phase SSMC | 30 | 30 | 0 | 0 |
| 6-phase VSI | 12 | 12 | 1 | 6 |
| 6-phase modular VSI | 24 | 24 | 1 | 6 |
| 6-phase SSMC | 36 | 36 | 0 | 0 |

IGBT: insulated gate bipolar transistor; DS-IGBT: diode series with IGBTs; BC: bulk capacitor; DR: diode in rectifiers

### 3.3 Single switch short circuit (SSSC)

The faulty conditions of SSSC could cause excessive phase current. For the VSI, the SSSC will cause a huge transient current and destroy the converter. However, in SSMC, the consequence will be better. In the 3-phase SSMC, the conduction period of current in the faulty phase is longer than that in the healthy phase, which results in a large transient torque at the time (Fig. 9). The current and torque waveforms for 4-, 5-, and 6-phase SSMCs are similar and thus are not presented here. The transient torque for all phase number drives rises by about 50% under this faulty condition, as can be seen in the simulation results.

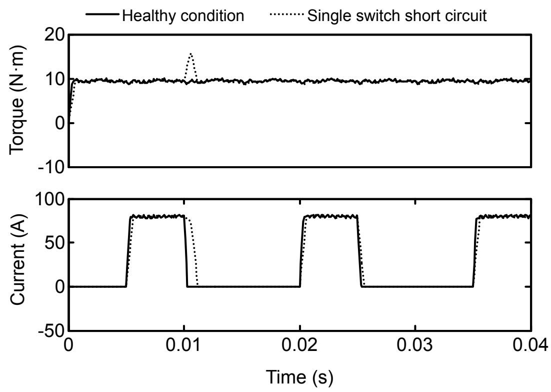


**Fig. 9 Output torque and faulty phase current waveforms of the 3-phase single sided matrix converter (SSMC) under healthy and single switch short circuit conditions**

It can be seen that the 5- and 6-phase SSMCs provide better performance over the others. Compared to the 6-phase drive, the remaining torque produced by the 5-phase drive under faulty conditions is slightly less. However, for the 6-phase drive, 20% extra power electronic components are required. As a result, the 5-phase SSMC drive is finally chosen as a compromise among fault tolerance, weight, and volume. The theoretical remaining average torques under different faulty conditions is summarized in Table 3. It can be seen that the SSMC has better performance than the modular VSI.

## 4 Prototypes

The 5-phase SSMC prototype was built. It consists of the brushless DC (BLDC) motor, five power boards, an interface circuit board, and hardware to

**Table 3 Comparison of theoretical remaining average torques between 5-phase modular VSI and SSMC under different faulty conditions**

| Condition | Remaining average torque | |
|---|---|---|
| | VSI | SSMC |
| SPOC | 80% | 90% |
| SSOC | 90% | 96% |
| SSSC | * | 150% (for 1/3 of the conducting time) |

SPOC: single phase open circuit; SSOC: single switch open circuit; SSSC: single switch short circuit. * The converter is destroyed

realize the control strategy (Figs. 10 and 11). Each power board consists of six IGBTs and associated gate drive circuits to realize the function of one SSMC basic unit. Five separate power boards are required for the 5-phase motor. The control board is based on an Actel field-programmable gate array (FPGA) and consists of nine A/D converter (ADC) channels and two D/A converter (DAC) channels. The FPGA chip used is an Actel A500k Pro ASIC (application specific integrated circuit), which combines the benefits of an ASIC with the advantage of being field programmable. A large number of configurable I/Os are provided for the complex system design. The current control loop is entirely implemented by the FPGA. A resolver interface board converts the analogue resolver signals into digital signals required by the FPGA control block. The voltage sensing circuit gets the voltage information and sends it to FPGA through the ADC. The control block in the FPGA generates the gate drive signals and sends through the current mirror board to the five power boards. A Texas Instrument C6711 Development Starter Kit has been employed to perform the overall system control and to acquire data from the FPGA during testing and calibration of the system. The DSP was mainly used, when necessary, to implement a speed control loop of the motor, which would be normally done by a repetitive execution unit (REU, a high reliability controller) on the aircraft.

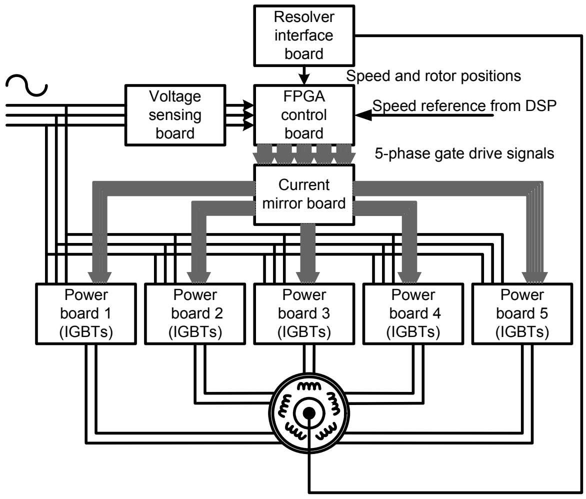


**Fig. 10 Block diagram of the single sided matrix converter (SSMC) prototype**

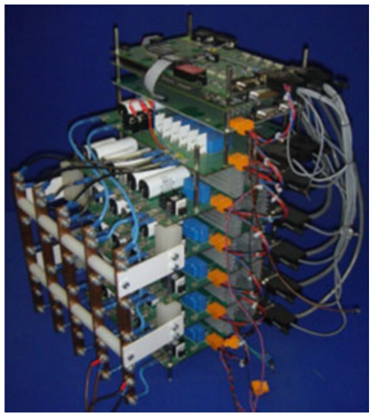

**Fig. 11 The 5-phase single sided matrix converter (SSMC) prototype**

**Fig. 12 Test rig**

## 5 Experimental results

The SSMC was connected to a BLDC motor coupled to a four-quadrant high speed test rig (Fig. 12). The test rig uses or absorbs power from the test BLDC motor using a 40 kW variable speed AC motor with a maximum speed of 20 000 r/min.

The SSOC test was done to prove the fault tolerance capability of the drive system. Fig. 13 shows the 5-phase current waveforms at 2000 r/min, 3 N·m under normal conditions with double band control. The current reference per phase is 11.33 A. Fig. 14 shows the 5-phase current waveforms when phase B is open circuit. The faulty phase has no impact on

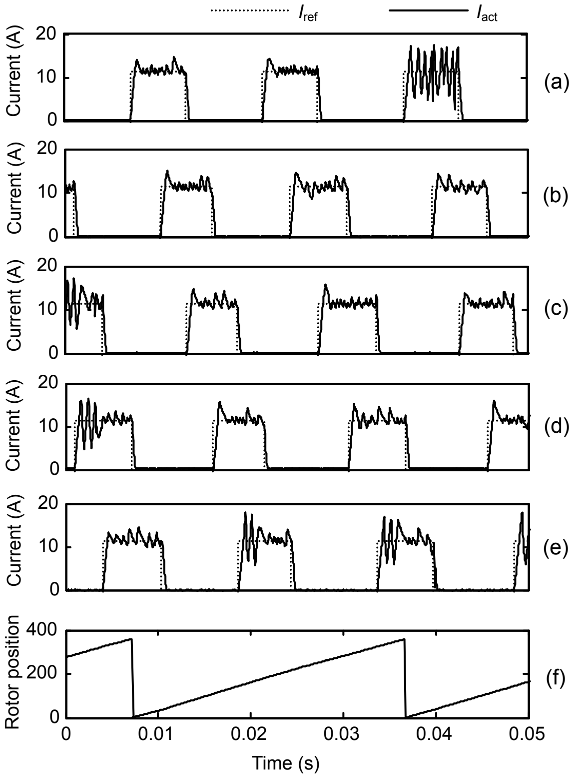


**Fig. 13 Double-band controlled 5-phase current waveforms (a–e) against rotor position (f) at 2000 r/min, 3 N·m under the healthy condition**
(a) Phase A; (b) Phase B; (c) Phase C; (d) Phase D; (e) Phase E

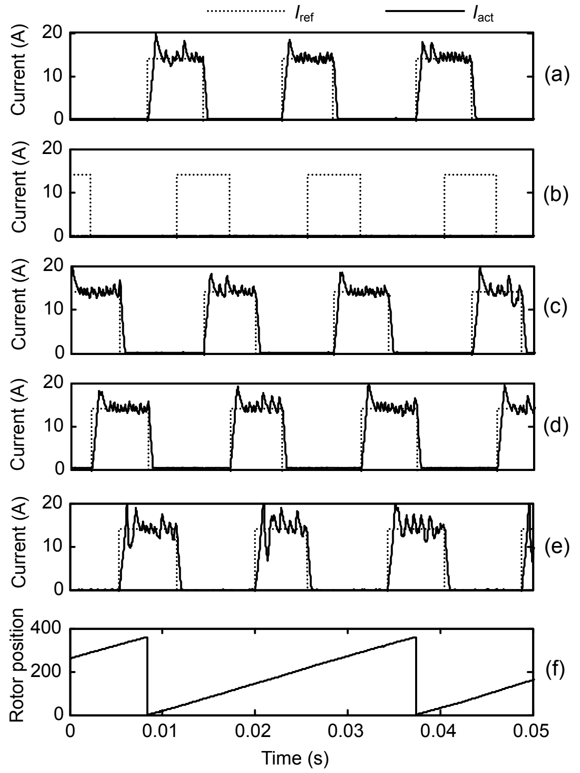


**Fig. 14 Double-band controlled 5-phase current waveforms (a–e) against rotor position (f) at 2000 r/min, 3 N·m under the single phase open circuit condition**
(a) Phase A; (b) Phase B; (c) Phase C; (d) Phase D; (e) Phase E

other healthy phases. The current reference per phase was increased to deliver the same level torque.

## 6 Conclusions

An single sided matrix converter (SSMC) with double band hysteresis control has been presented for flight control actuation systems. The fault tolerance of the SSMC has been investigated individually. The SSMC with the higher number of phases is more fault tolerant with the penalty of the increased size/volume. The dynamic simulation results proved that the SSMC provided greater fault tolerance in the case of the single switch open and short circuits compared to the traditional VSI. The 5-phase SSMC design was validated as a compromise between fault tolerance and converter size/volume. In the future, the optimized controller strategies in dealing with faults would provide worthwhile research.

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