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# Fault Tolerant Inverter For High Speed Pmbldc Drive In Aerospace Applications

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**Abstract:** The Permanent Magnet Brushless DC (PMBLDC) motors is an ideal choice for the applications that require high efficiency, high reliability, high Power-to-weight ratio and high performance. The BLDC motor is highly reliable since it does not have any brushes to wear out, they are light weight motors and the life expectancy is over 10000 hours when operated in rated conditions. These motors are therefore used in Aerospace applications, as they can withstand extremely high temperatures (around 2000˚C), high shock and load vibrations and supply continuous power. The motor is coupled to the constant speed propeller in an aircraft and provide high speeds, high torque and high performance operation even under faults. The faults are mostly due to the power semi-conductor devices in the inverter supplying the BLDC motor. Faults could be open-circuit or short circuit fault in the semiconductor switch. In this paper, a buck converter and a fault tolerant inverter with one leg made up of two capacitors and an extra redundant leg is used for the BLDC motor. The Buck converter and the Fault protective circuit ensures that the motor operation is not disturbed even during fault conditions.

## 1 INTRODUCTION

The inverter supplying the BLDC drive is made of MOSFET switches. Switch faults – Open circuit and closed circuit faults cause the disturbance in the motor operation. In this work, circuit reconfiguration is done by adding a Capacitor leg and an extra redundant leg to the inverter and the various faults arte simulated and the characteristics are studied. Since we have the Buck converter, the fault is overcome almost instantaneously. Due to capacitor leg supplying the Phase A of motor, this acts like a Four switch Three phase inverter. With this approach, the fault is isolated effectively and the secondary fault occurrence is avoided.

## 2 EXPERIMENTAL APPROACH / MAJOR CONTENT OF THE PAPER

The input to the PMBLDC motor is supplied by a Buck converter containing an Inductor and Capacitor. The input voltage to Buck converter is DC Voltage. The 3 legs of the inverter are connected to the 3 phases of the motor and a fault protective circuit is also connected (Fig1) and an extra redundant leg is also present (Fig 2).

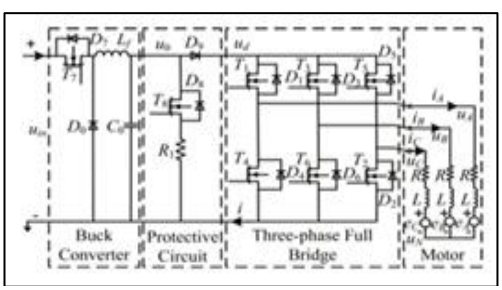


*Fig 1 : Buck converter, Three phase inverter and BLDC motor combination circuit*

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proposed circuit (Fig. 3), the Phase A leg of the inverter is replaced by Capacitors as shown in the circuit diagram.

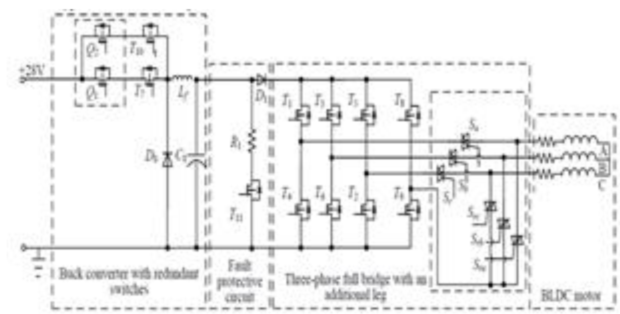


***Fig 2:** Existing fault-tolerant inverter topology for BLDC drives with additional redundant leg*

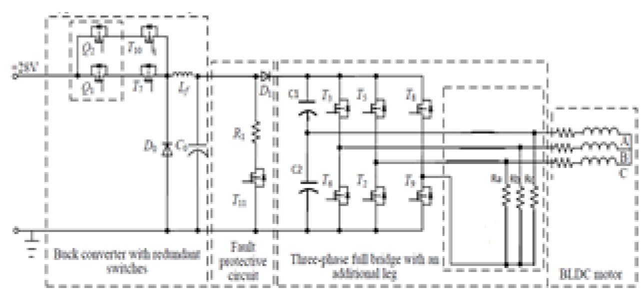


***Fig 3:** Proposed Fault-tolerant inverter topology for BLDC drives with one phase supplied by Capacitor leg*

About 50% faults in inverter are due to power switches like MOSFET's and IGBT's. Usually the four common faults are classified as,

1) Open circuit fault in the Buck converter switch (F1)
2) Short circuit fault in the Buck converter switch (F2)
3) Open circuit fault in Three phase inverter switch (F3)
4) Short circuit fault in Three phase inverter switch (F4)

In this work, only Open circuit and Short circuit faults in the inverter switch are simulated and analyzed using MATLAB with and without the protective circuit. The Open and short-circuit Faults in Buck converter switch (faults F1,F2) do not interrupt the 3-phase inverter operation, and thus the operation of the BLDC motor is not hindered.

## 3 RESULTS AND DISCUSSION

### 3.1 Simulations and Results

Simulation are done based on the proposed fault tolerant inverter with the BLDC motor, in both open loop and closed loop. In the sections 3.1.1, 3.1.2. 3.1.3 and 3.1.4 – the faults are created in MATLAB. But it is to be noted that, even during the Fault occurrence, the motor operation is not much disturbed as shown in Figs- 5d, 6b, 7d, 8b.

**Normal open loop operation:** In the normal open loop mode, phase A of the 3 phase inverter is made up of Capacitor legs. The other 2-phases are having MOSFET switches. This is 120 degree conduction mode of the inverter. An extra redundant leg is connected, it will act whenever a leg fails – due to open/short circuit faults. The modes of operation will change due to the presence of the Capacitor leg (supplying Phase A).

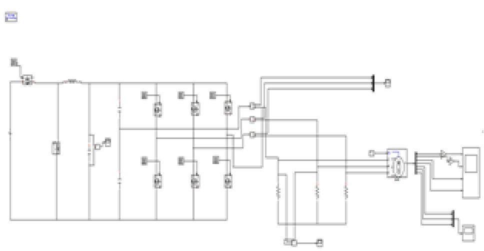

***Fig 4a)*** *Normal Operation Open loop –circuit diagram*

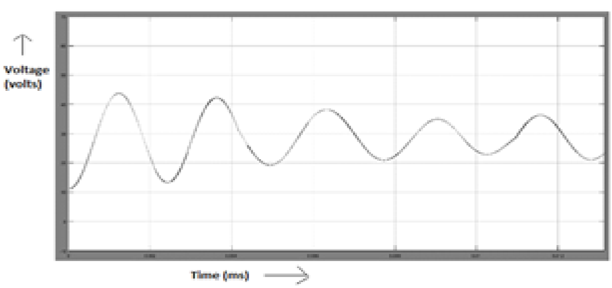


***Fig 4b*** *i)DC-link voltage (Vdc = 35V)*

In the open loop operation, the Motor Torque = 75 Nm, Motor Speed = 1250 rpm, Stator back emf = 50V

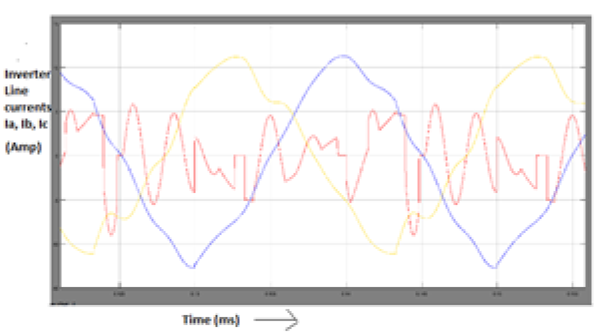


***Fig 4b ii)*** *Ia, Ib and Ic currents from 3- phase inverter (Ib, Ic = 11A)*

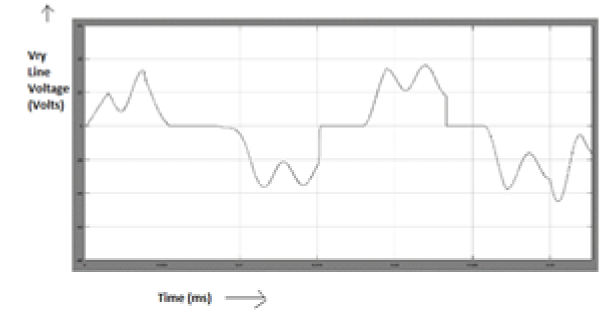


***Fig 4c i)*** *& ii) RY Line voltage = 35V*

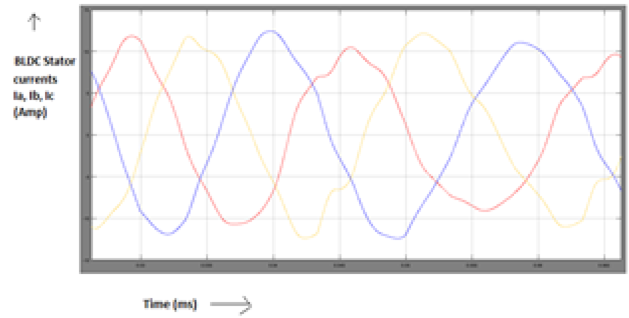


***Fig 4c ii)*** *RY Line voltage = 35V; BLDC Motor stator currents – Ia, Ib, Ic = 12A*

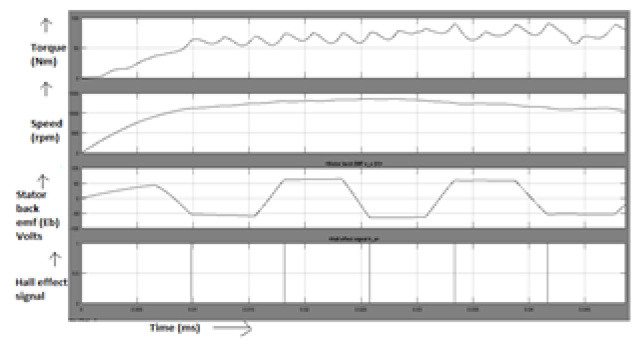


***Fig 4d)*** *BLDC MOTOR Output – Open loop operatio*

**Open circuit fault in 3-phase inverter switch (F3) :** The circuit diagram in Fig 5a shows that the Open circuit fault had occurred in the T3 thyristor of the inverter, supplying Phase B of the BLDC motor.

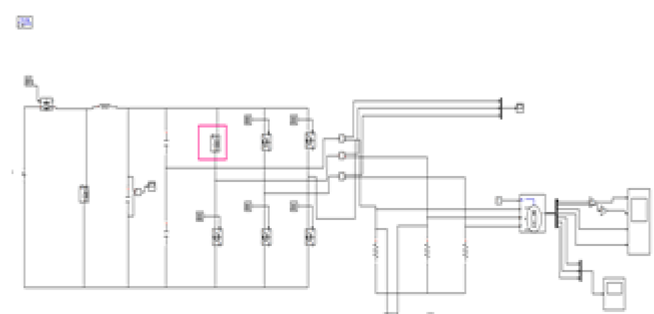

***Fig 5a)*** *Open circuit fault in 3-Phase inverter switch (F3)– circuit diagram*

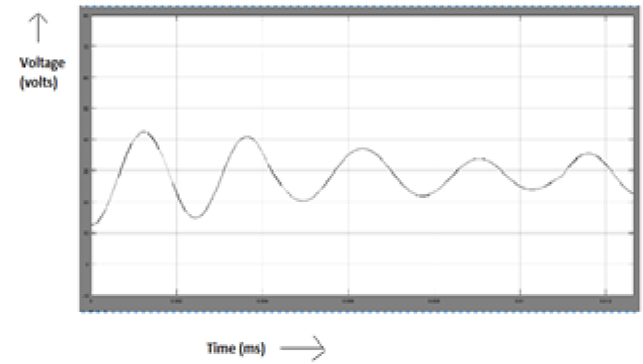


***Fig 5b i)*** *& ii) DC-link voltage (32V)*

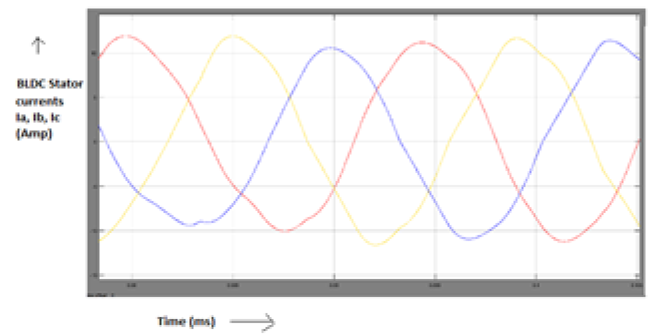


***Fig 5c ii)*** *BLDC Motor stator currents – Ia, Ib, Ic during Fault F3 (Ib, Ic = 11A*

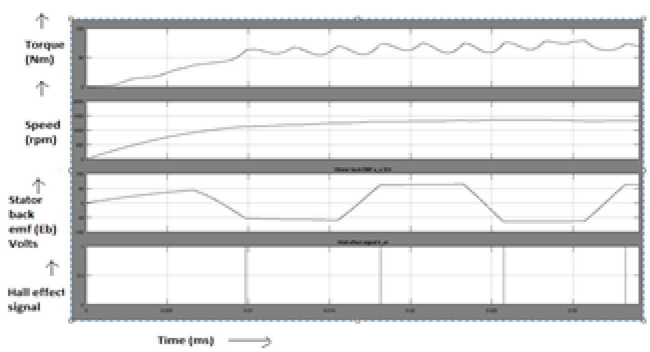


***Fig 5d)*** *BLDC MOTOR Output - F3 fault operation*

Motor Torque = 80 Nm, Motor speed = 1100 rpm and Stator Back emf = 52V In the Figure 7d, the Torque, speed, stator back emf waveforms are shown during the Open –circuit fault in the inverter switch (T3) – F3 Fault. It is to be noted that due to the presence of the redundant leg, the normal continuous operation of the drive is maintained even during F3 fault. Open circuit fault in 3-phase inverter switch (F3) with protective circuit: The figure 8a, shows the open circuit fault in T3 switch with the fault protective unit.

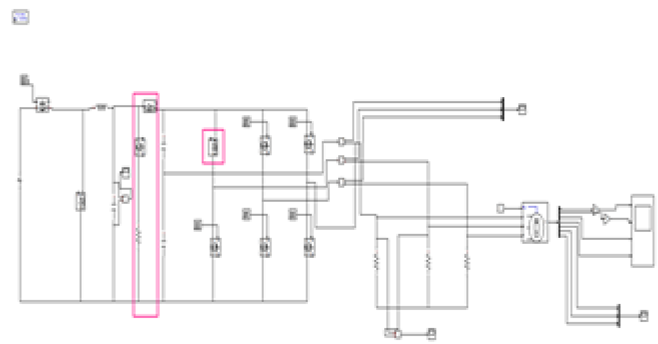

***Fig 6a)*** *Open circuit fault in 3-Phase inverter switch (F3) with protective circuit: circuit diagram*

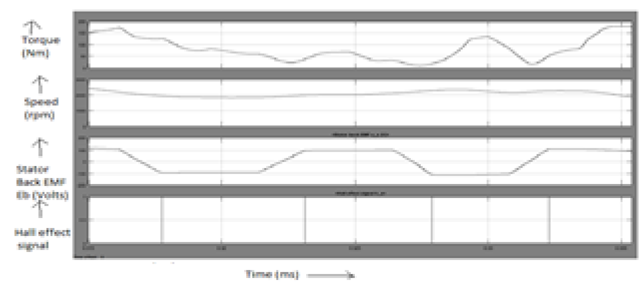


***Fig 6b)*** *BLDC MOTOR Outputs - F3 fault with protective circuits*

The outputs are: Motor Torque = 100 Nm, Motor Speed = 1800 rpm, Stator Back emf = 100V

Motor Torque and speed are increased when protective circuit is added during F3 fault. Short circuit fault in 3-phase inverter (F4): The Figure 9a shows the inverter short-circuit fault (F4) in the T3 switch. During the short-circuit fault, there is a low impedance path created and overcurrent condition occurs and current will flow through all the 3 phases. But the duration of the overcurrent is minimized significantly, due to the buck converter and redundant inverter leg.

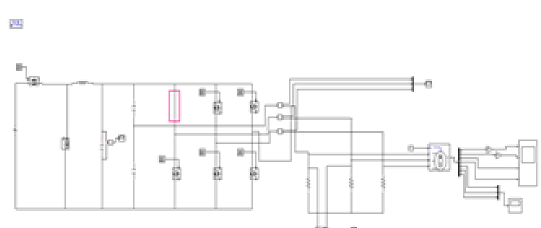

***Fig 7a)*** *Short circuit fault in the 3-Phase inverter switch (F4)– circuit diagram*

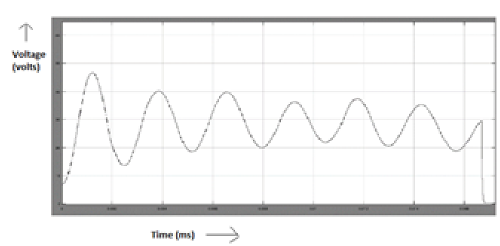


***Fig 7b i)*** *DC-link voltage*

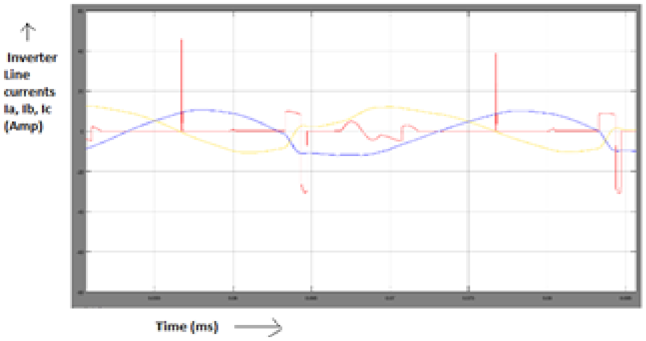


***Fig 7b** **ii**) Ia, Ib and Ic currents from 3-Phase inverter during F4 fault (Ia = 48A, Ib, Ic = 10A)*

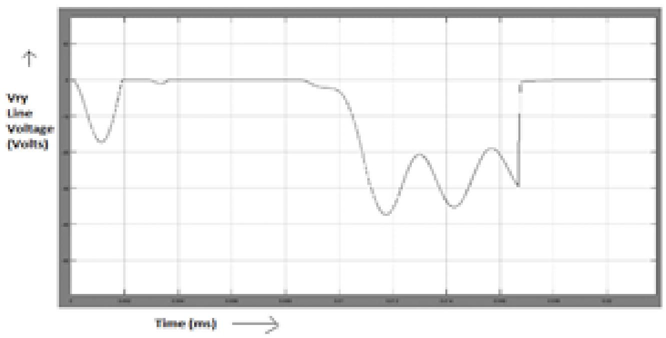


***Fig 7c i)** RY Line voltage*

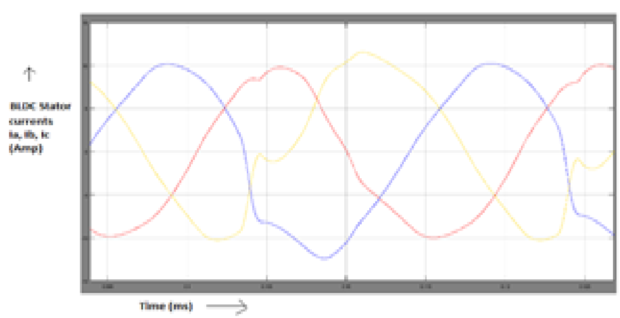


***Fig 7c ii)** BLDC Motor stator currents – Ia, Ib, Ic during F4 fault (Ia, Ib, Ic = 11A)*

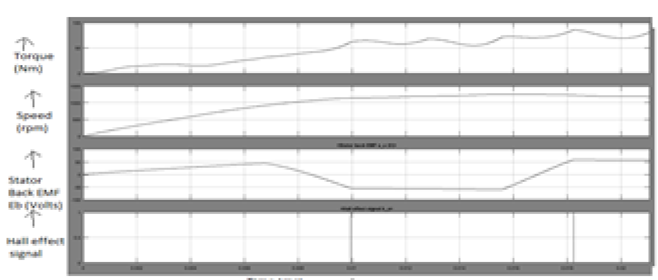


***Fig7d)** BLDC MOTOR Outputs - during F4 fault*

The output parameters are:Motor Torque = 85 Nm, Motor speed = 1200 rpm, Stator Back emf = 52V

**Short circuit fault in 3-phase inverter switch (F4) with Protective circuit:** The figure 8a shows the F4 fault (short circuit fault in inverter switch) in T3, with a protective circuit

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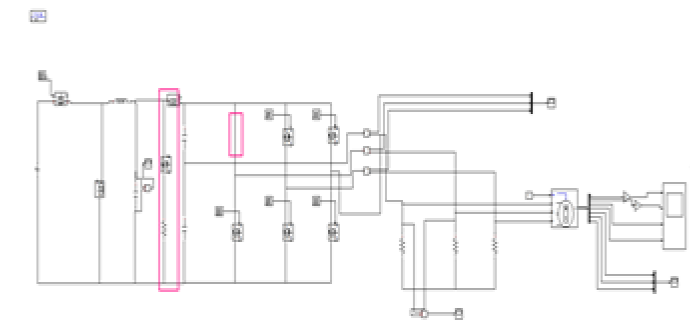


***Fig8a)** Short circuit fault in 3-Phase inverter switch (F4) with protective circuit: circuit diagram*

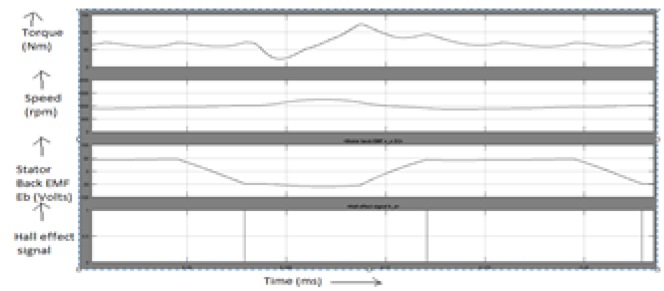



***Fig 8b)** BLDC MOTOR Outputs - Torque, current, Stator Back EMF and Hall effect sensor signal during F4 fault with protective circuit*

The output parameters are: Motor Torque = 95 Nm, Motor speed = 1000 rpm, Stator Back emf = 50V. Motor Torque is increased when a protective circuit is added during F4 fault.

Normal Closed loop operation – with Hall effect sensors : In the closed loop operation, the BLDC motor output is sensed through the Hall effect sensor, its output is passed to a PI Controller, then the 3 phase to 2 phase conversion takes place, and then the pulses are generated to trigger the Phase B and Phase C legs only. Phase A leg doesn't need trigger pulses, since the leg is made up of Capacitors. In the closed loop operation, the motor speed is increased Motor Torque produced = 95 Nm, Speed of the motor = 1360 rpm, Stator back emf = 50V.

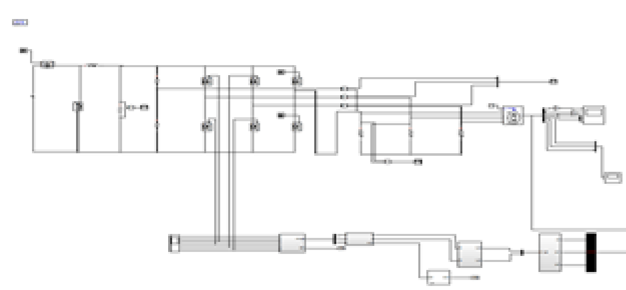


***Fig 9** Normal Operation Closed loop with Hall effect sensors–circuit diagram*

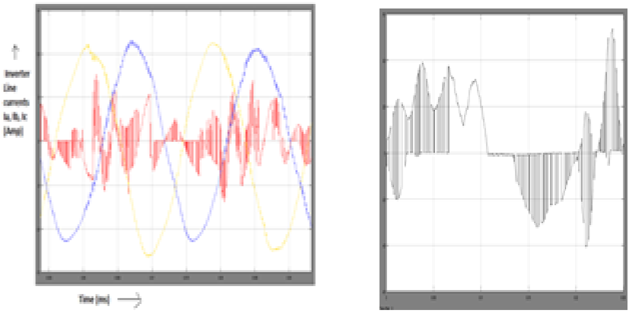


***Fig 10 a)*** *DC-link voltage(38V) and Ia, Ib and Ic currents from 3- phase inverter –Closed loop (Ib, Ic = 11A) diagram*

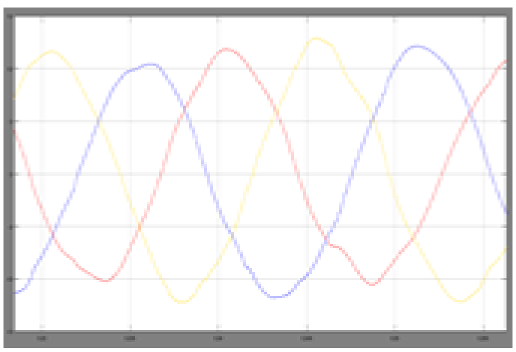


***Fig 10 b)*** *RY Line voltage, BLDC Motor stator currents – Ia, Ib,* Ic– Closed loop operation

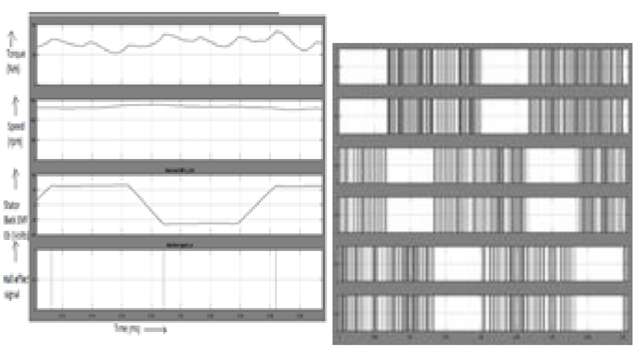


***Fig 11 a****) BLDC MOTOR Outputs– Closed loop operation and b) Hall effect signals to trigger the Phase B & Phase C (Close*

### 3.1 Hardware Setup

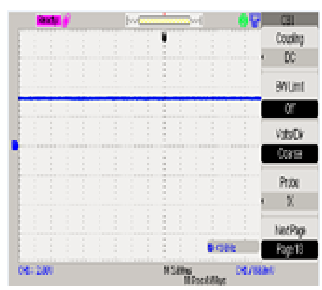
In the hardware, a buck converter, 24V PMBLDC motor and PIC microcontroller(PIC16F887) was used. The DC input voltage is 24V. Inverter is made up of MOSFET Switches. Both Normal operation and Fault operation are implemented. An Open circuit fault is created in inverter switch manually and the motor still executes even under the faulty conditions.

**Hardware Kit and DSO Outputs**

***Fig 12*** *Hardware setup – with PIC Microcontroller*

The Figure 12 shows the hardware kit including Buck converter, 4-leg inverter and BLDC drive. Figures 13a, 13b, 13c, 13d shows the output parameters of the inverter. Figure 13a gives the DC Link voltage, from the buck converter, this is input to the 3-phase inverter. Figure 13b shows the inverter pulse during fault. For the hardware implementation we use below listed components.

(i) PIC Microcontroller 16F887 (ii) Power supply transformers (iii) Buck converter (iv)Three-phase inverter (v) Permanent magnet Brushless DC Motor (PMBLDC) (vi)Buffer, driver circuits (vii) Opto-coupler (viii) Bi-directional switches.



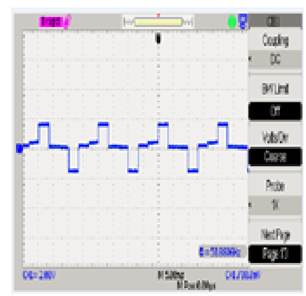


***Fig 13a*** *DC Link output voltage waveform* ***Fig 13b*** *Fault pulse*

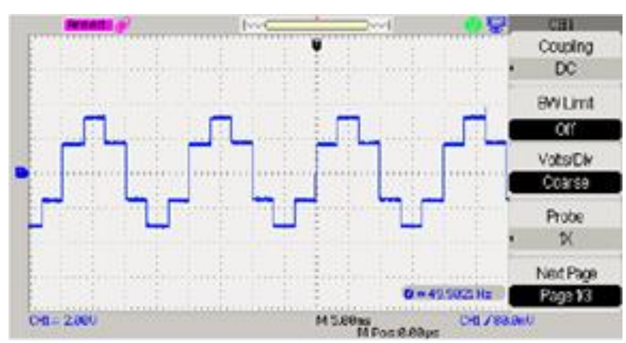



***Fig 13c*** *Line voltage across the inverter*

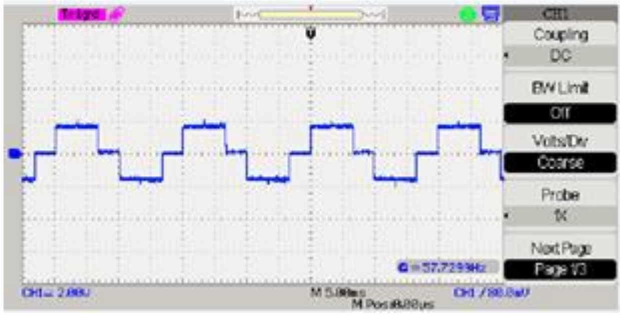



***Fig 13d*** *Phase voltage across inverter*

## 4 CONCLUSION

In this paper, the open circuit and short circuit faults in the Inverter switch are studied and simulated. A fault-tolerant topology is designed to control the BLDC motor used in Aerospace applications. In this work, a fault-tolerant topology with a Capacitor leg in the inverter and an additional phase leg is designed to control the high speed low inductance BLDC motor used in Aircraft applications. The fault occurrance is overcome almost instantaneously, due to the presence of Buck converter and the redundant leg in the inverter. Both the simulation and experimental results prove that the output parameters of BLDC motor such as torque and speed are maintained constant even during faulty conditions. Therefore the operation of the drive is continuous even during disturbances and an effective fault-isolation is achieved. This fault-tolerant control ensures high reliability and continuous operating capacity even under the faulty situations. Since the human intervention is impossible in aerospace applications, this type of control is essential to maintain quiet and stable operation of the drive

## 5 REFERENCES

[1] Haitao Li; Wenzhuo Li; Hongliang Ren "Fault-tolerant inverter for high speed low inductance BLDC drives in Aerospace application" IEEE Transactions on Power Electronics, Volume: 32, Issue: 3, Pages: 2452 - 2463, Year: 2017

[2] Jiancheng Fang; Wenzhuo Li; Haitao Li; Xiangbo Xu "Online inverter fault diagnosis of buck-converter BLDC motor" IEEE Transactions on Power Electronics Volume: 30, Issue: 5, Pages: 2674 - 2688, Year: 201.

[3] Şafak Ekmen; Bekir Fincan; Murat Imeryuz "A BLDC motor drive with Four switch three phase inverter", 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA) Pages: 804 - 808, Year: 2016

[4] M. Beltrao de Rossiter Correa; C. Brandao Jacobina; E. R. Cabral da Silva; A. M. Nogueira Lima "An induction motor drive system with improved fault tolerance", IEEE Transactions on Industry Applications, Volume: 37, Issue: 3, Pages: 873 - 879, Year: 2001

[5] Chia-Chou Yeh; Nabeel A. O. Demerdash "Induction motor drive systems with fault tolerant inverter-motor capabilities", 2007 IEEE International Electric Machines & Drives Conference, Volume: 2, Pages: 1451 - 1458 , Year: 2007

[6] Rammohan Rao Errabelli; Peter Mutschler "Fault tolerant voltage source inverter for permanent magnet drives", IEEE Transactions on Power Electronics, Volume: 27, Issue: 2, Pages: 500 - 508, Year: 2012