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Control and Implementation of Fault Tolerant Brushless DC Motor Drive for Automation Industries Application

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Abstract: The sensorless based brushless DC motor has generate continuous power supply even under the faulty situation in inverter. In order to improving the performance and continuous operation of BLDC motor, a fault control circuit is used to protect and continous power supply to motor. In this study, the fault tolerant control and soft start capabilty of BLDC motor is of great importance for its continuous operating capacity. Fault tolerant topology composed of an additional phase leg and a fault protective circuit for the high-speed low-inductance BLDC motor. The analysis covers a short circuit and overvoltage phenomenon after the switch faults, a new fault isolation and system reconfiguration method is presented. The switch is used to fault identification and isolate the faulty leg and supply the power to the additional leg. Simulation performance are verified and fault indication are using MATLAB/Simulink results and hardware implemented using embedded controller to verify about soft start, fault identification and fault tolerant performance of BLDC drive system.

Key words: Brushless DC motor (BLDC), sensorless control, Space Vector Modulation (SVM), fuzzy logic control, Proportional Integral control (PI) control, TRIAC, fault reconfiguration, fault tolerant

INTRODUCTION

In recent years the brushless DC motor has mostly used in industrial application because of high torque, better speed versus torque characteristics, high dynamic response, high efficiency and reliability, long operating life (no brush erosion), noiseless operation and reduction of Electromagnetic Interference (EMI) and use simple control technique. In motor drive application the important factor is continuous, high performance and distortion less output and also regulate the characteristics of BLDC motor speed (Fernandes, 2017; Li *et al*., 2016; Gleissner and Bakran, 2016). The growing demand for continuous power supply in BLDC motor when fault occurs. The fault is detected by using the switch and isolate the fault in inverter side in the way of using TRIAC across the inverter and the BLDC motor. The additional leg is used to replace the faulty section and the performance is improved (Sobanski and Kowalska, 2014; Nguyen *et al*., 2016).

In conventional the speed of the motor is reduced during the fault but in proposed motor has maintain the speed and also, the performance is maintained. The asymmetrical SVM is used to control and isolate the fault. It can decrease the amplitude and also reduce the harmonics in inverter fed BLDC motor (Nallamekala and Sivakumar, 2016; Chen *et al*., 2017). The brushless DC motor is a synchronous electric motor and is similar to DC motor. The proposed motor has a linear relationship between current and torque, voltage and speed, electronically, controlled commutation system, instead of having a mechanical commutation which is typical of brushed motors (Farhadi *et al*., 2017; Salehifar *et al*., 2016; Liu *et al*., 2016). For component-based techniques, solid-state switches are individually protected with gate signal monitoring, overcurrent and overheating schemes, some of which are current standard features of industrial power converters (Rajkumar *et al*., 2017; Fang *et al*., 2015; Mirafzal, 2014). These techniques are integrated into the inverter analog circuitry to detect switch abnormalities relatively fast, i.e., <10 μsec. In system-based techniques, inverter current and voltage waveforms are examined to identify fault type and location. These techniques can further be categorized into waveform analysis and algorithmic techniques (Tashakori, 2016; Fabri *et al*., 2015; Shu *et al*., 2017).

In inverter the fault diagnosis in the power electronics switches by measuring the voltage measurement and fed with switches the voltage is zero the fault protection device remove the pulse in the fault leg and supply the pulse in the additional leg and also, gate pulse in the TRIAC switches. The stator voltage is balanced even though the fault occur in the inverter. The continuous supply to the BLDC motor under the fault

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condition. The space vector modulation is used for steady performance and also improving the efficiency of motor drive systems.

MATERIALS AND METHODS

Proposed fault analysis in inverter fed bldc motor: The proposed sensorless brushless DC motor supply utilize the extra leg in inverter terminal for continuous power production. The high frequency and high current ripple causes to decrease the efficiency and also, reduce the motor performance. The fault occur in the three phase inverter will decrease the efficiency and have discontinuous power supply. The fault tolerant can be estimated by the fault occur in phase to phase. During the fault the volatge across the phase is zero and sense the fault by using volatge measurement across the phase. The control of the proposed motor topology use sensorless adaptive neuro fuzzy system and the speed is calculated by the back emf method. The space vector modulation on self tuning neuro fuzzy system based control is use to generate the pulse and fed into the inverter. In order to avoid the harmonics by using the SVM control method. Figure 1 shows the block diagram of proposed circuit topology.

Brushless DC motor: The inverter fed BLDC motor has used to analyse the fault detection and fault isolation technique. The sensorless control method is used in the inverter circuit. The speed and torque of the motor is calculated by using the back emf method. During the fault the stator voltage is reduced to zero. In order to balance the voltage by using the fault protective element in the proposed self tuning based sensorless BLDC motor. Figure 2 shows the three phase inverter fed BLDC motor. The stator winding of proposed sensorless based BLDC motor is explained in the following Eq. 1-3.

$$U_{xn} = R_x i_x + \frac{d}{dt}\left(L_x i_x + L_{yx} i_y + L_{zx} i_z\right) + e_x \tag{1}$$

$$U_{yn} = R_y i_y + \frac{d}{dt}\left(L_{xy} i_x + L_{yy} i_y + L_{zy} i_z\right) + e_y \tag{2}$$

$$U_{zn} = R_z i_z + \frac{d}{dt}\left(L_{xz} i_x + L_{yz} i_y + L_{zz} i_z\right) + e_z \tag{3}$$

Where:

R = The stator resistance per phase for phase a-c

L = The stator inductance per phase and presume to be phase a-b

$i_x i_y$ and i_z = The stator current

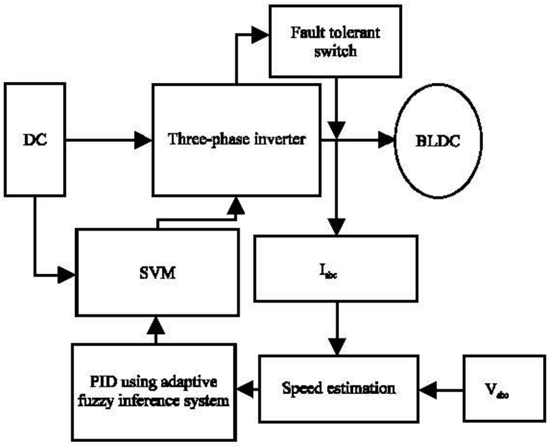

Fig. 1: Block diagram of proposed circuit topology

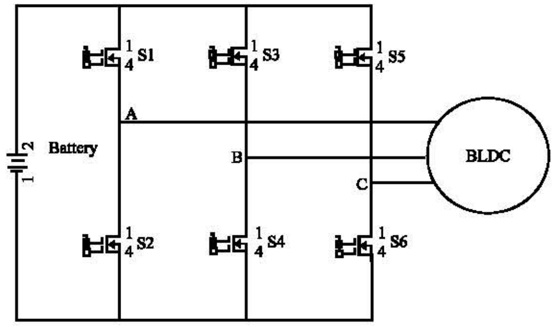

Fig. 2: Three phase inverter fed BLDC motor

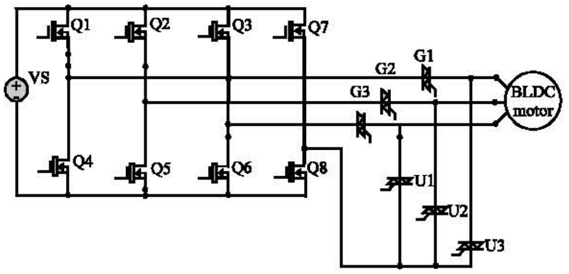

Fig. 3: Fault tolerant in inverter fed BLDC motor

Proposed fault tolerant circuit: Figure 3 shows the fault tolerant in inverter fed BLDC motor. The phase to phase fault occurs in inverter. During fault the stator voltage is zero and isolates the fault by using the switch and TRIAC. The fault occurs across the AB phase the voltage across the phase is reduced to zero and pulse through the faulty leg is disconnected and additional inverter leg is introduced to balance the stator voltage. The TRIAC is used between the inverter and BLDC motor. The six anti parallel diode is used to balance the voltage. The TRIAC

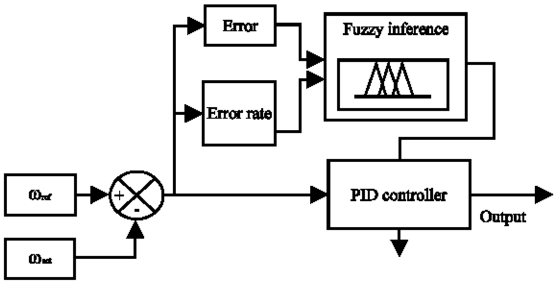

Fig. 4: Representation of self tuning PID based on neuro fuzzy ω_{ref} = Reference speed, ω_{act} = Actual speed

and additional leg has used to balance the voltage during the fault. The fault occurs in phase and switch will identify the fault and it will cut the pulse across the Q1, Q4 and G1. The switch will supply, the pulse in switch Q7, Q8 and U1. The voltage across the inverter is maintained.

Self tuning control using adaptive neuro fuzzy-PID: The proposed self tuned adaptive neuro fuzzy PID control is used to control the inverter fed BLDC motor. The speed and torque of motor is estimated by using the back emf method. The space vector modulation is enhanced the system performance and also, decrease the current and voltage ripple. The general representation of self tuning PID based on neuro fuzzy is shown in Fig. 4. The K_p, K_d, K_i values are evaluated in Eq. 4-6:

$$K_p = \frac{K_p\text{-}K_{p,\,min}}{K_{p\,max}\text{-}K_{pmin}} \tag{4}$$

$$K_d = \frac{K_p\text{-}K_{d,\,min}}{K_{d\,max}\text{-}K_{dmin}} \tag{5}$$

$$K_i = \frac{K_p^2}{K_d+\alpha} \tag{6}$$

The fault tolerant circuit in brushless DC motor has utilized the space vector modulation based on adaptive self tuning neuro fuzzy PID control method is shown in Fig. 5. The actual speed is compared with reference speed the resultant speed is fed into neuro fuzzy PID for estimate the quadrature axis and fed into the space vector for generating the pulse of three phase inverter. The control method has cleared the fault and enhances the motor performance.

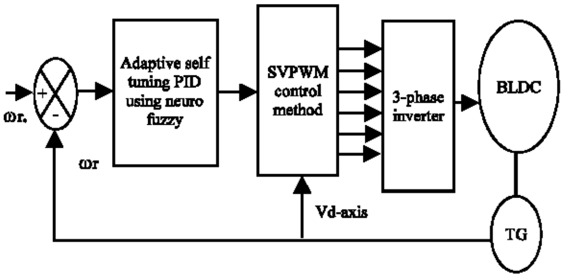

Fig. 5: Proposed SVPWM based vector control schemeusing adaptive neuro fuzzy self tuning of PID ωr = Actual speed, ωr* = Reference speed, Vq-axis = Voltage in quadrature axis, vd-axis = Voltage in direct

Table 1: Proposed fuzz rules for self tuning PID control

De/e	NB	NM	NS	PB	PM	PS	ZO
NB	K_p-B K_d-B α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2
NM	K_p-S K_d-B α-3	K_p-B K_d-B α-2	K_p-B K_d-S α-3	K_p-B K_d-B α-3	K_p-B K_d-B α-3	K_p-B K_d-S α-2	K_p-B K_d-S α-3
NS	K_p-S K_d-B α-4	K_p-S K_d-B α-3	K_p-B K_d-B α-4	K_p-S K_d-B α-4	K_p-S K_d-B α-3	K_p-B K_d-B α-3	K_p-B K_d-S α-2
PB	K_p-B K_d-S α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2	K_p-B K_d-S α-2
PM	K_p-S K_d-B α-3	K_p-B K_d-B α-3	K_p-B K_d-S α-2	K_p-S K_d-B α-3	K_p-B K_d-B α-3	K_p-B K_d-S α-2	K_p-B K_d-S α-2
PS	K_p-S K_d-B α-4	K_p-S K_d-B α-3	K_p-B K_d-B α-3	K_p-S K_d-B α-4	K_p-S K_d-B α-3	K_p-B K_d-B α-3	K_p-B K_d-S α-2
ZO	K_p-S K_d-B α-5	K_p-S K_d-B α-4	K_p-S K_d-B α-3	K_p-S K_d-B α-5	K_p-S K_d-B α-4	K_p-S K_d-B α-3	K_p-B K_d-B α-3

K_p-B = Proportional gian Big, K_d-B = Derivative gian Big, K_p-S = Proportional gian Small, K_d-S = Derivative gian Small, α is a constant and varies from 2-5

Table 2: Switching state of SVPWM

Switching state (3 phases)	On-state switch	Definition
[111]	S1, S3, S5	0
[000]	S4, S6, S2	
[100]	S1, S6, S2	$\vec{V}_1 = \frac{2}{3}V_d e^{j0}$
[110]	S1, S3, S2	$\vec{V}_1 = \frac{2}{3}V_d e^{j\frac{\pi}{3}}$
[010]	S4, S3, S2	$\vec{V}_1 = \frac{2}{3}V_d e^{j\frac{2\pi}{3}}$
[011]	S4, S3, S5	$\vec{V}_1 = \frac{2}{3}V_d e^{j\frac{3\pi}{3}}$
[001]	S4, S6, S5	$\vec{V}_1 = \frac{2}{3}V_d e^{j\frac{4\pi}{3}}$
[101]	S1, S6, S5	$\vec{V}_1 = \frac{2}{3}V_d e^{j\frac{5\pi}{3}}$

The adaptive neuro fuzzy system is implemented by fuzzy rules and produced due to the load and parameter variation in BLDC motor is given in Table 1. The switching state of SVPWM is given in Table 2. The motor parameters are given in Table 3. The space vector diagram for two level inverter is shown in Fig. 6.

Table 3: Motor parameters

Parameters	Values
Nominal power (HP)	$P_n = 10$
Nominal speed (rpm)	$w_n = 1800$
Nominal torque (N.m)	$T_n = 39.5$
Indutance in d-axis (H)	$Ld = 22.1.\ 10^{-3}$
Indutance in q-axis (H)	$Lq = 91{:}1.\ 10^{-3}$
Armature winding resistance (Ω)	$R = 6.51.\ 10^{-1}$
Flux linkage (Wb)	$\lambda = 67.09.10^{-1}$
Coulomb friction coefficient (N-m)	$F_c = 10^{-1}$
Viscous friction coefficient (N.m sec/rad)	$F_v = 1.10^{-1}$
Static friction coefficient (N.m)	$F_s = 6.4.10^{-1}$
Static friction decreasing rate (rad/sec)	$\eta_s = 2$
Rotor and load inertia (kg. m^2)	$j = 1.10^{-1}$
Number of pole pairs	$P = 2$

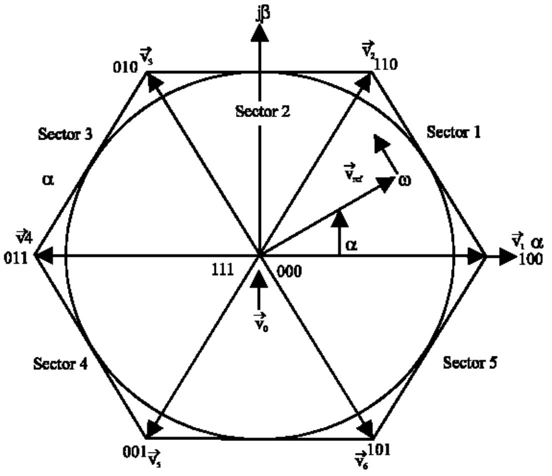

Fig. 6: Space vector diagram for two-level inverter

RESULTS AND DISCUSSION

The overall simulation circuit based on fault tolerant in self tuning sensorless control fed BLDC drive system.The fault occurs between the phases of the inverter. The fault is isolated by using the ideal switch for regulation of stator voltage of brushless DC motor. The sensorless based self tuning PID controller is used in the inverter circuit. The speed is estimated by using the back emf method. The speed control and maintain the stator voltage is achieved by proposed sensor less based self tuning control for increasing the motor performance under fault condition, variable load and parameters conditions. The proposed self tuning PID based on neuro fuzzy control is shown in Fig. 7. The stator voltage of BLDC motor during fault is shown in Fig. 8. The stator current of proposed BLDC motor is shown in Fig. 9. The stator voltage of BLDC motor based on fault protection is shown in Fig. 10. The speed characteristics of BLDC motor is shown in Fig. 11. The torque characteristics of BLDC motor is shown in Fig. 12.

Hardware implementation: The proposed fault tolerant brushless DC motor is implemented in hardware for verifying the fault protection of proposed drive system. The proposed inverter is controlled using dsPIC33FJ32MC202 digital signal controller platform and results are obtained in this study. The inverter circuit is implemented using power MOSFET IRF 840 and for

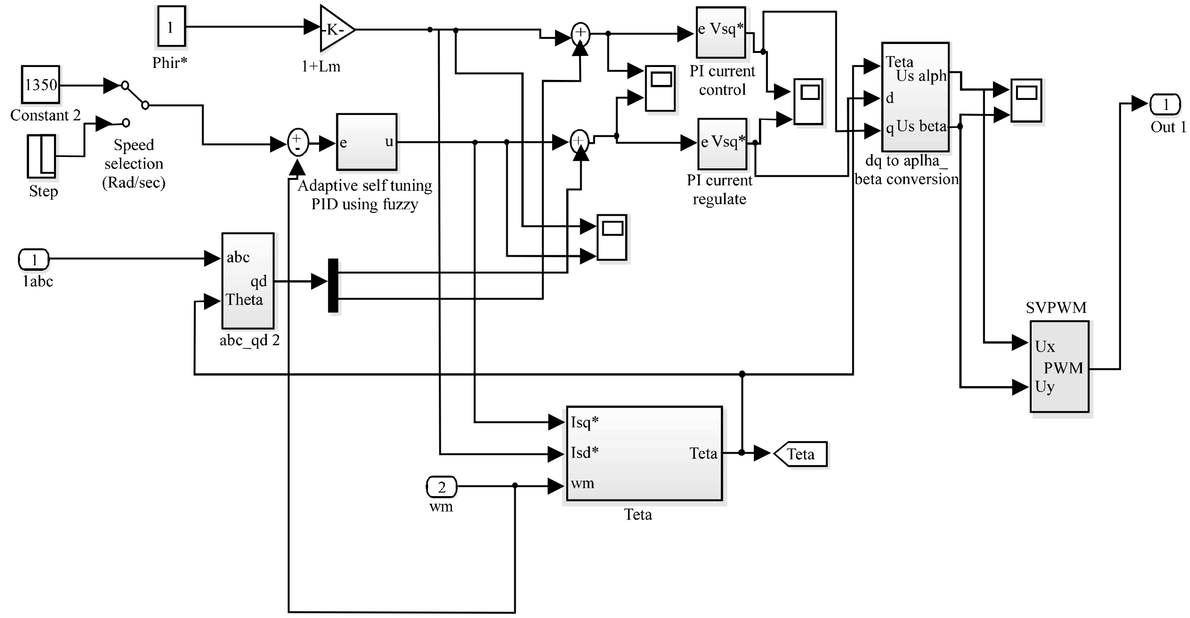

Fig. 7: Proposed self tuning PID based on neuro fuzzy control

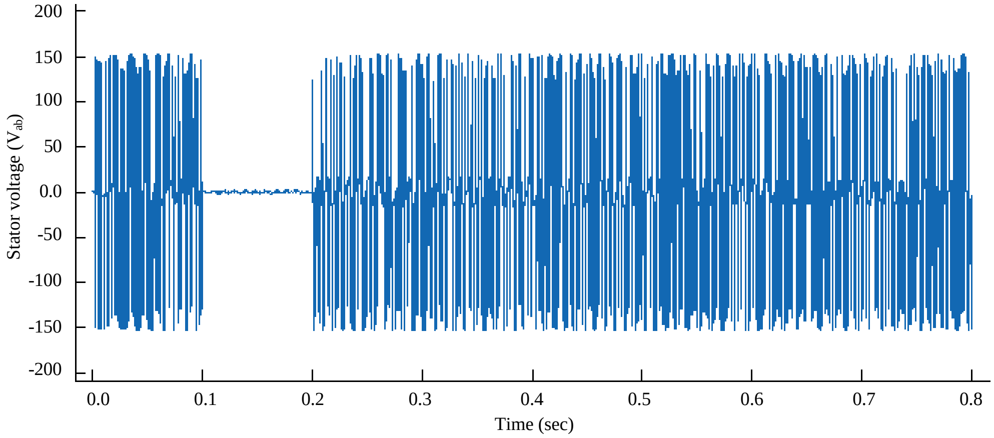

Fig. 8: Stator voltage of phase AB during fault

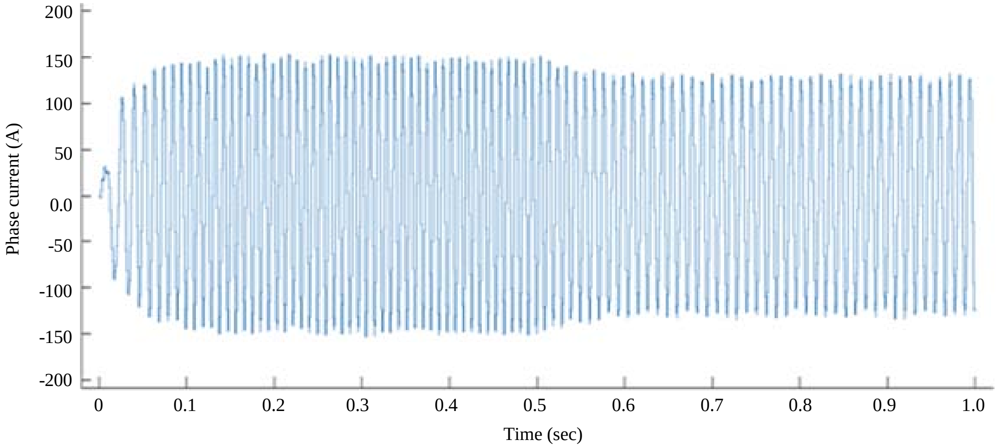

Fig. 9: Stator current of proposed BLDC motor

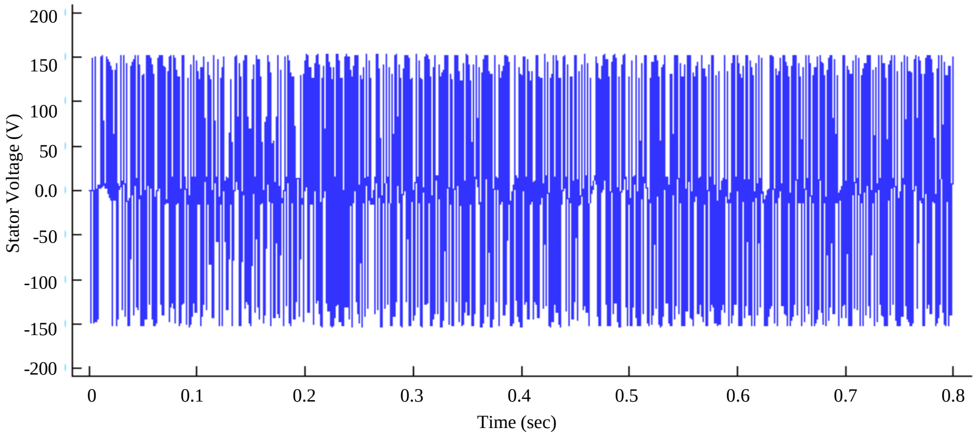

Fig. 10: Stator voltage of proposed BLDC motor based on fault protection

driving these MOSFET’s 8-pin opto coupler TLP-250 IC is used. The hardware of proposed method is shown in Fig. 13. The stator voltage is shown in Fig. 14. The fault signal in inverter is shown in Fig. 15. The speed of the brushless DC motor is shown in Fig. 16. The proposed fault protection in the inverter based DC drive system has reduced the stator voltage during fault.

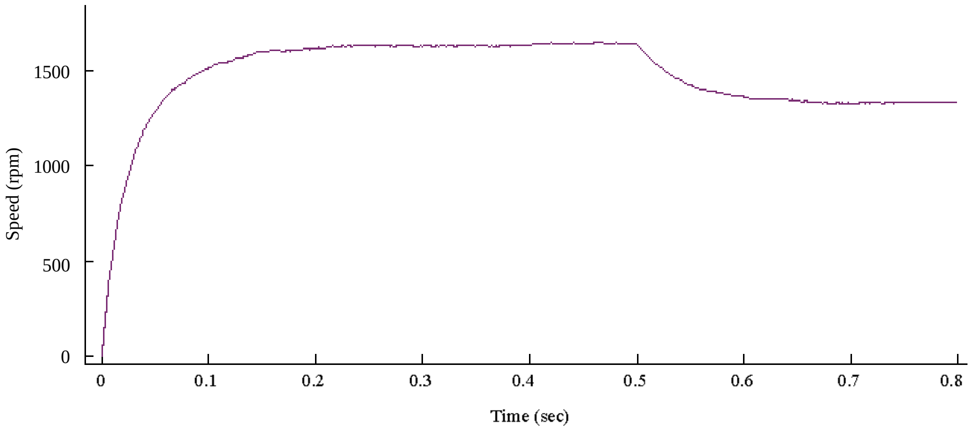

Fig. 11: Speed characteristics of BLDC motor

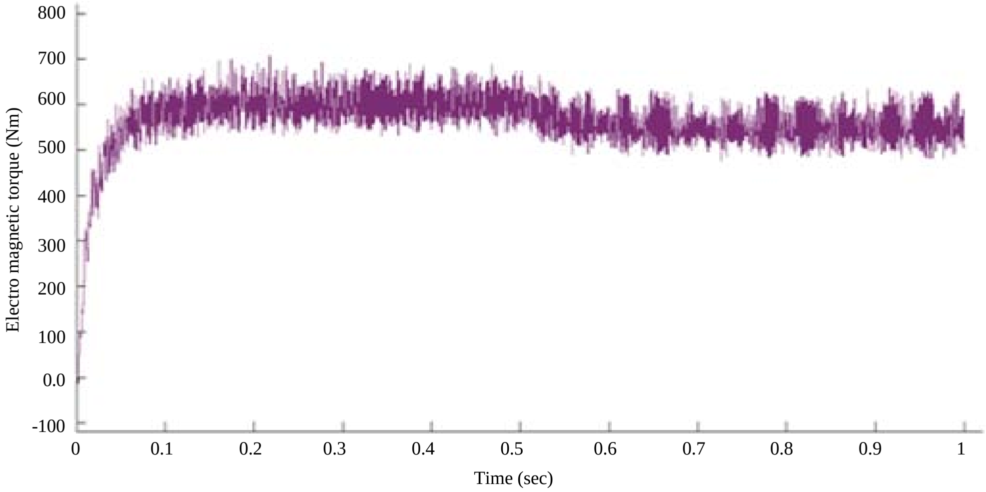

Fig. 12: Torque characteristics of BLDC motor

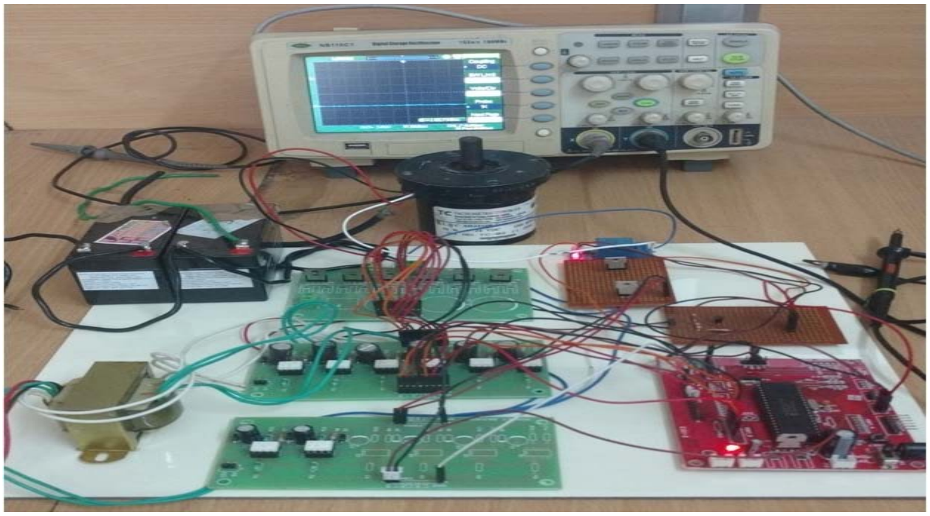

Fig. 13: Hardware circuit of proposed method

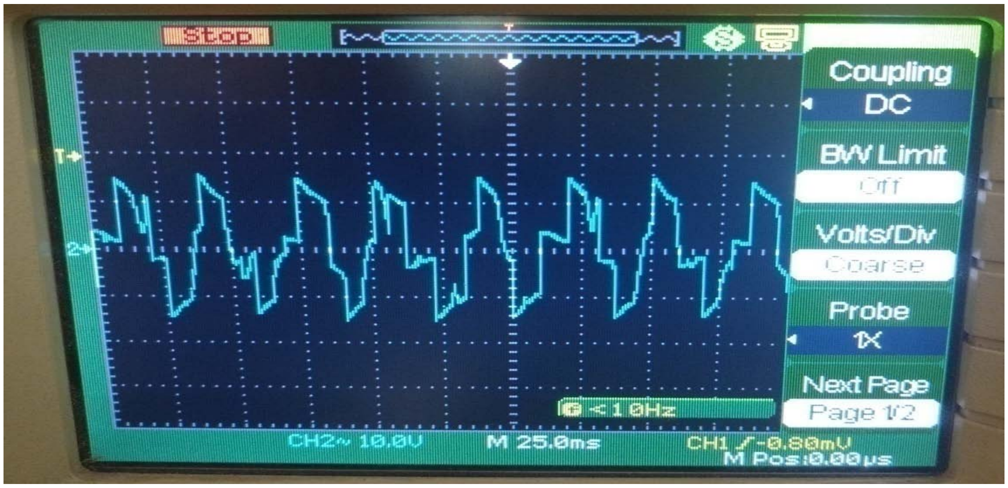

Fig. 14: Stator voltage of brushless DC motor

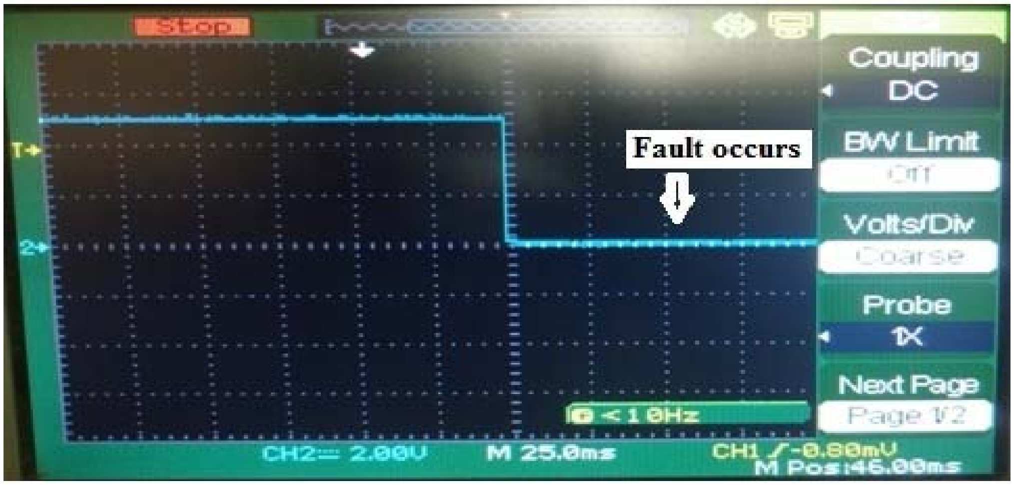

Fig. 15: Fault control signal for tolerant circuit

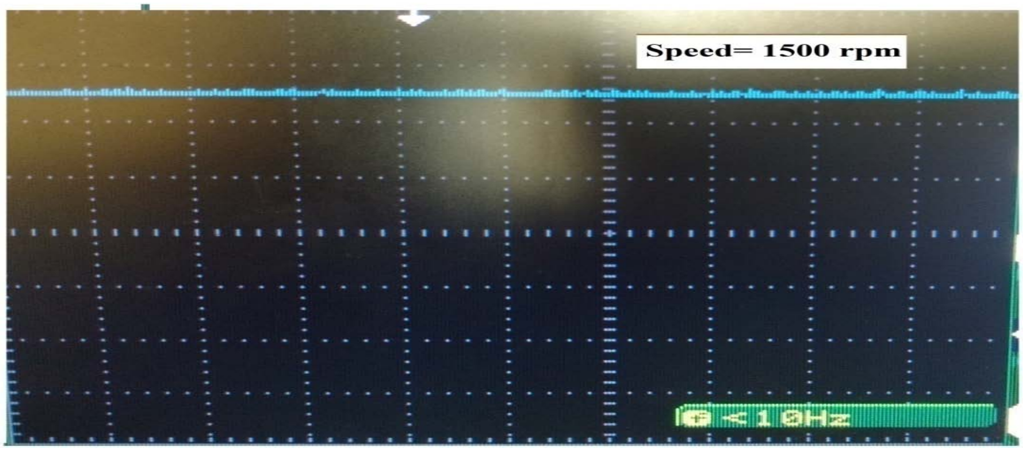

Fig. 16: Speed characteristics of brushless DC motor

CONCLUSION

In automotive application the brushless DC motor has used for high speed application and the self tuning PID based sensorless space vector modulation control is achieved the steady state capability of BLDC motor. The fault occurs between the phases of inverter causes the reduction of voltage during fault. The fault tolerant circuit is used to improve the stator voltage of brushless DC motor. The back emf method is used to compute the speed and torque of the proposed motor configuration. If fault arise, motor load and internal parameters variation is changed, general control scheme is not able to control for wide load and parameters variation motor drives. The performance of proposed circuit and control configuration under fault tolerant performance is verified and implemented by using MATLAB/Simulink. The drawn results are proved about their performance and capable of variable load conditions and fault condition.

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