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Fault Tolerant Capability of Five Phase BLDC Motor with Ten Step commutation

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ABSTRACT: The permanent magnet brushless DC motor found more popularity in industrial, residential and aerospace applications because of their inherent advantages over conventional brushed DC motor. To impact rotation to this motor electronics are nece=ssary. The paper mainly concentrated on multiphase machines and developed the ten step commutation logic for five phase BLDC motor. The four quadrant operation and fault tolerant capability of five phase BLDC was evaluated with ten step commutation logic and the results are presented. The simulation of presented commutation logic was carried out in MATLAB/SIMULINK and the results are validated with the experimental results. The hardware implementation of ten step commutation was done in an AT89C51 microcontroller platform and the results are presented.

KEYWORDS:commutation, multiphase, ten step commutation, microcontroller

I. INTRODUCTION

The multiphase PMBLDC motor found more importance in medium and high power drives because of their inherent advantages of high reliability, fault tolerant capability, reduced current per phase, reduced amplitude and increased frequency of torque pulsation over the convention three phase BLDC motor [1]-[7]. These motors find wide application in variable speed drives because of the advancement in solid state devices and the availability of rare earth alloy permanent magnet [8],[9]. As the name indicates the multiphase system is a system with numerous numbers of windings or circuits. The winding arrangement and the construction of multiphase motor are similar to that of a three phase motor except the number of windings arranged in the stator[10]. The number of stator winding is equal to the number of phases and these windings can be arranged either in star or in delta fasion. [1],[7]-[10].To impact rotation to a BLDC motor its winding have to be energized in a proper sequence and the order of energization will depends on the position of rotor. The hall sensors are used to achieve the position information and these sensors are arranged in a stator winding [11], [12]. For the proper operation of BLDC motor, a suitable commutation sequence and a power electronic converter is necessary. For BLDC motors, the type of commutation scheme adopted determines the torque ripple at the output which attributes to one of the major losses [13]. There are two types of conventional commutation schemes, such as trapezoidal commutation and sinusoidal commutation.

In BLDC motors the phase windings are arranged in trapezoidal fashion in order to generate the trapezoidal BEMF waveform and in sinusoidal or distributed winding arrangement to get a sinusoidal back EMF. Based on the back EMF pattern, two types of commutation techniques such as trapezoidal commutation and sinusoidal commutation are developed. In sinusoidal commutation, all the phases are conducting at any instant of time. The current through each phase is smooth and continuous which reduces the torque ripple [11]-[13]. The implementation of Sinusoidal commutation is complex because of the requirement of highly precise encoders for getting the position information.

Trapezoidal commutation or six step commutation is one of the simplest commutation schemes which can implement with the information achieved from the hall sensors [11]. In this commutation scheme only two phases is energized at a time and the remaining one phase will be in a non-energized condition. The switching sequence was developed with the concept, that the hall sensor pattern and back EMF waveform are aligned each other.

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This paper extents the concept of six step commutation in three phase BLDC motor to ten step commutation in five phase BLDC motor [10]. The proposed commutation sequence for five phase BLDC motor was developed with the same concept of six step commutation logic [14]- [19]. The simulation results are presented by using MATLAB/Simulink as the simulation tool and its results are validated with the experimental results. To evaluate the fault tolerant capability of five phase BLDC motor, the experiment was conducted when the motor operates in four phase and three phase by releasing the phases in running condition and examined the performance of motor. The hardware implementation of ten step commutation was carried out in an AT89C51 microcontroller platform and the experimental results are also presented.

II. COMMUTATION SCHEME

The conventional DC motor commutes itself with the use of a mechanical commutator whereas brushless DC motor needs electronic commutation for the direction control of current through the windings. Different types of commutation schemes are available to impact rotation to a BLDC motor. Among them the most common is trapezoidal commutation and sinusoidal commutation.

Sinusoidally commutated brushless controllers attempt to drive the three phase motor windings with three currents that vary smoothly and sinusoidally. This eliminates torque ripple and commutation spikes associated with trapezoidal commutation [13]. This control method provides better performance and efficiency at lower speed. The main drawback associated with this method is the requirement of highly precise encoders for position sensing. The trapezoidal commutation logic is one of the simplest methods to drive a three phase BLDC motor. It is also called as six step commutation, since it requires six steps to complete one electrical cycle [12].This method utilizes hall sensors for position information. The switching sequences corresponding to the Hall sensor pattern are developed from the concept that the back EMF waveform and hall pattern are aligned each other. In this method two phases are conducting at every instant of time and the remaining one phase will be in non-energized condition. This method is very popular because of the simplicity of its control algorithm and with reduced switching loss.

The six step commutation logic in a three phase system can be utilized in a five phase system as ten step commutation logic. The proposed commutation is one of the simplest forms of commutation logic which enables the four quadrant operation of the motor. The switching sequence of presented topology was developed with the concept that the hall devices are aligned properly with the generated back EMF voltage [10]. Here each stator windings are displaced by 72 electrical degrees and at every 36 degree two windings get energized with positive power, two with negative power and the remaining one will be in the non-energized condition. The sequence of energization of stator winding will depends on the rotor position. The position information can achieved from the hall sensors mounted in stator winding. The hall sensors provide a logical high or low signal depending upon the rotor North Pole or South Pole passes [14]. Ten possible combinations of hall sensor patterns are available for a five phase BLDC motor. The proposed commutation logic requires ten step to complete one electrical cycle and have the name ten step commutation. The number of electrical cycles require to complete one mechanical rotation will depend on the number of rotor pole pairs.

TABLE I
SWITCHING SEQUENCE OF TEN STEP COMMUTATION IN CLOCKWISE DIRECTION

Ha	Hb	Hc	Hd	He	A	B	C	D	E
1	0	0	1	1	0	1	1	-1	-1
1	0	0	0	1	-1	1	1	0	-1
1	1	0	0	1	-1	0	1	1	-1
1	1	0	0	0	-1	-1	1	1	0
1	1	1	0	0	-1	-1	0	1	1

0	1	1	0	0	0	-1	-1	1	1
0	1	1	1	0	1	-1	-1	0	1
0	0	1	1	0	1	0	-1	-1	1
0	0	1	1	1	1	1	-1	-1	0
0	0	0	1	1	1	1	0	-1	-1

The switching sequence required for operating the motor in clockwise and counter clockwise direction are different. Table I indicates the hall sensor pattern and the corresponding switching sequence developed for operating the motor in anti-clockwise direction and Table II indicates the switching sequence in clockwise direction. In table I corresponding to the hall position 10011, the phase B and C are conducting with positive current and phase D and E with negative current, and the phase A in a non –energized condition, where as in table II corresponding to the same hall position A and E are energized with positive power, phase B and C with negative power. The proposed commutation scheme provides a quasi-square shaped current waveform with its value coming to zero twice in an electrical cycle. This commutation scheme offers simplicity in implementation with reduced switching loss and also offers the operation of motor in both direction with same speed.

TABLE II
SWITCHING SEQUENCE OF TEN STEP COMMUTATION IN ANTI-CLOCKWISE DIRECTION

Ha	Hb	Hc	Hd	He	A	B	C	D	E
1	0	0	1	1	1	-1	-1	0	1
1	0	0	0	1	1	0	-1	-1	1
1	1	0	0	1	1	1	-1	-1	0
1	1	0	0	0	1	1	0	-1	-1
1	1	1	0	0	0	1	1	-1	-1
0	1	1	0	0	-1	1	1	0	-1
0	1	1	1	0	-1	0	1	1	-1
0	0	1	1	0	-1	-1	1	1	0
0	0	1	1	1	-1	-1	0	1	1
0	0	0	1	1	0	-1	-1	1	1

III. SIMULATION RESULTS

The mathematical model of five phase BLDC motor drive was developed in MATLAB/SIMULINK [4]-[6], [10]and the simulation of proposed ten step commutation scheme was carried out. The simulation parameters used are L=0.7mH and R=0.7 ohm.The duration of conduction of each switch was controlled by a PWM signal of 10 KHz frequency, generated by comparing the command signal with triangular waveform of frequency 10 KHz. The hall sensor pattern and the corresponding switching sequence developed for a five BLDC motor was entered using embedded MATLAB functions. The current through each phase winding was modelled using the equation (1).

$$I_i = \frac{1}{L_i} \int V_{iN} - E_{iN} - I_i R_i \qquad (1)$$

where i = A, B, C, D and E

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The instantaneous back EMF in BLDC motor is given in equation (2) where, ω is the rotor mechanical speed and θ is the rotor electrical position.

$$Back\ EMF, E = K_b f(\theta)\omega \qquad (2)$$

The torque developed by the motor is given in the equation (3)

$$Torque, T = K_t \emptyset I \qquad (3)$$

Fig. 1 represents the angle of rotation of BLDC motor.The angle obtained is compared with 360 degree and whenever the angle is greater than 360 degree the integrator is reset to the initial value. From the angle of rotation we get the positions and the Fig.2 represents the position of rotor. If rotor moves from 0 to 360 degree, the position is 1 and for the next 36 degree movement the position is 2 and similarly for other angles. The back EMF waveform of presented topology has a trapezoidal shape as shown in Fig.3 and the current through phase A winding of motor is given in Fig 4. Here the current waveform has a quasi-square shape with its value comes to zero twice in an electric cycle.

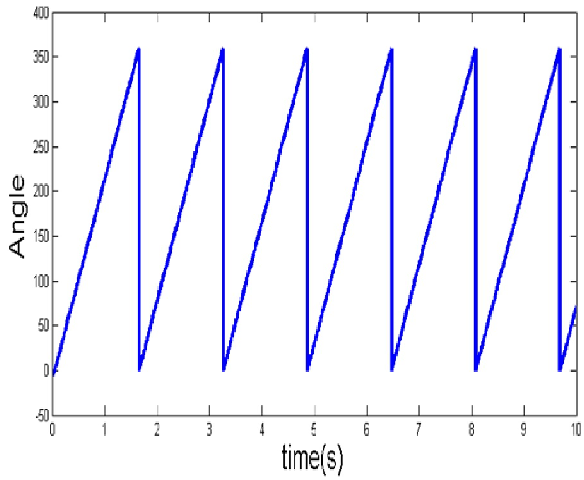

Fig.1 Angle

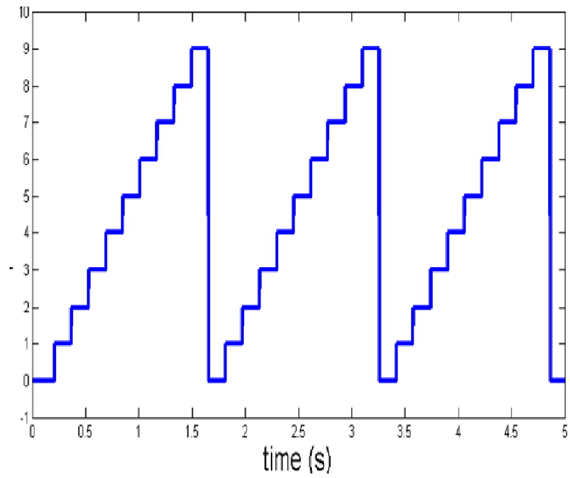

Fig.2 position Diagram

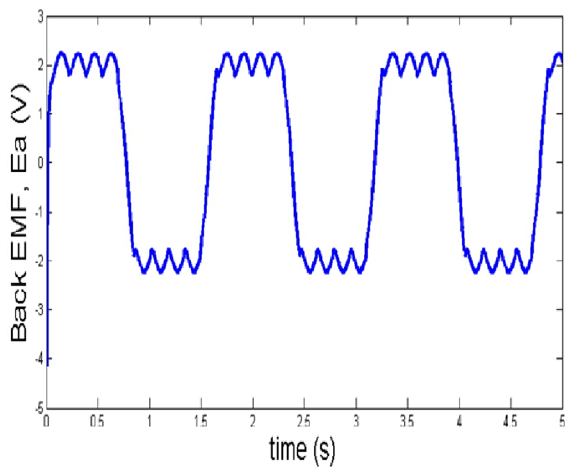

Fig.3 Back EMF waveform

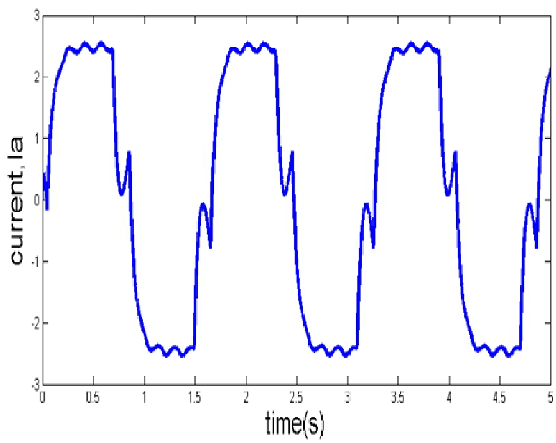

Fig.4 Current waveform of phase A winding

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IV. EXPERIMENTAL RESULTS

The experimental setup of five phase BLDC motor drive with ten step commutation logic was developed as shown in fig.5. It includes a PWM and dead band generator, a precision source to provide the command signals, and a five phase BLDC motor connected to five legged inverter. The experiment was carried out in a five phase, 28V, 600 rpm BLDC motor and the PWM pulses for the MOSFET switches in the five legged inverter driven byIR2110 driver circuit are generated by the microcontroller.The proposed commutation sequence corresponding to the hall sensor pattern and the PWM and dead band signals are implemented in an AT89C51 microcontroller platform. It is a 40 pin IC, which can be reused for many times. A PWMsignal of 10KHz frequency and a dead band signals of 4 microseconds are developed using analogue setup. The experiment was carried out at different conditions five phase, four phase and three phase to check the reliability and fault tolerant capability of motor with the presented ten step commutation logic.

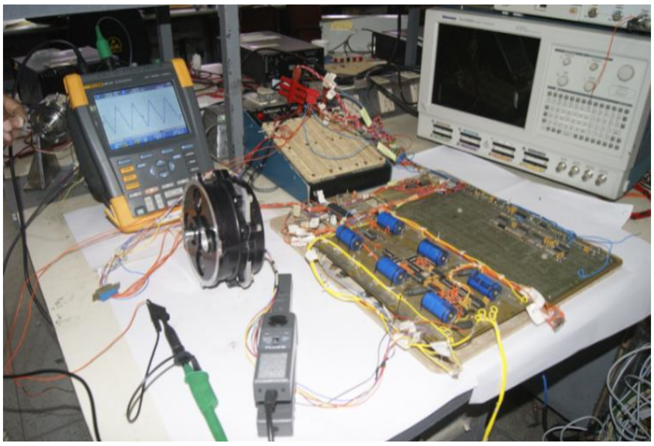

Fig.5 Experimental setup

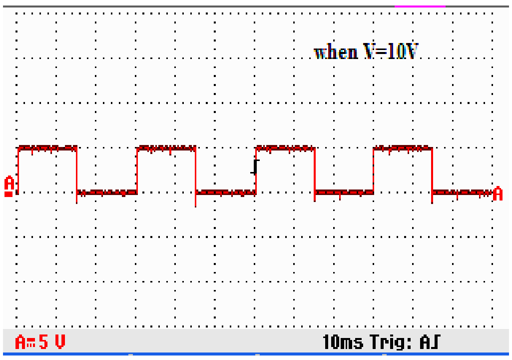

Fig.6Hall sensor pattern when motor operates as five phase

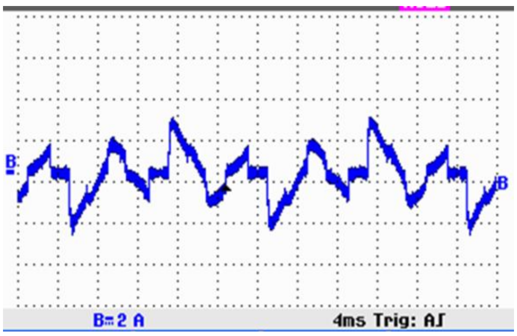

Fig.7 Current waveform when motor operates as five phase

The speed of rotation of motor is evaluated with the halls sensor pattern.Fig.6 shows the hall sensor pattern of five phase BLDC motor when motor operates at 10V. The current through phase A winding of five phase BLDC motor when operates with ten step commutation is as shown in fig.7. Here the current waveform has a quasi-square shape with its value comes to zero twice in an electrical cycle [12] as predicted by the simulation. Fig 8 and fig.9 shows the hall sensor pattern and the current of Phase A winding, when motor operates at four phase and three phase. From the wave form its cleared that the speed of operation of motor remains unchanged even though it's one or two phases get failed during its operation.

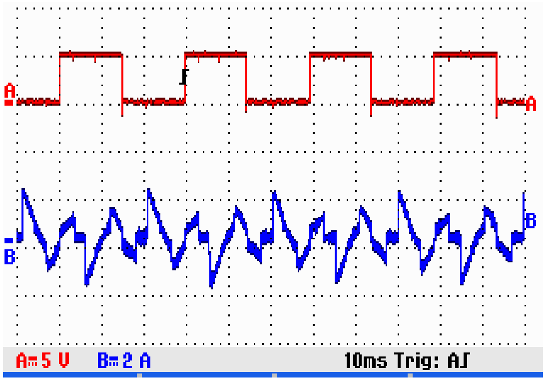

Fig.8 Hall pattern and current when motor operates as four phase

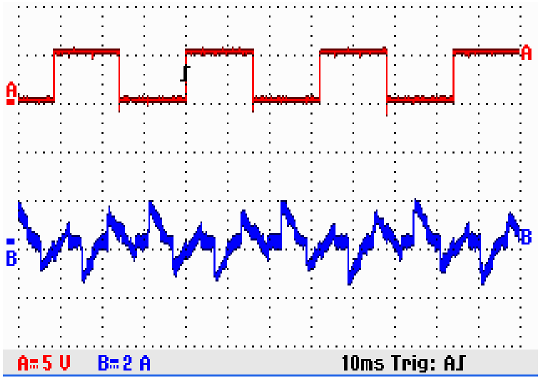

Fig.9 Hall pattern and current when motor operates as three phase

. The reliability and the fault tolerant capability of motor with ten step commutation was analysed by operating the motor at different conditions five phase, four phase and three phase and at different voltages 10V,15V and 20V. The performance of motor at different conditions is examined and the results are tabulated in tableIII, table IV and tableV. The speed of rotation of motor in clockwise and anti-clockwise direction with ten step commutation was evaluated by changing the command signal and it is observed that the presented commutation scheme can operate the motor with same speed in both direction and established the four quadrant operation of motor with proposed commutation scheme.

TABLE III
EXPERIMENTAL RESULTS WHEN OPERATES AS FIVE PHASE

Clockwise Direction			
Voltage (V)	**Current(A)**	**Time(ms)**	**Speed(rpm)**
10	0.61	30	250
15	0.88	20	375
20	1	15	500
Anti-Clockwise Direction			
10	0.58	30	250
15	0.85	20	375
20	0.96	15	500

TABLE IV
EXPERIMENTAL RESULTS WHEN OPERATES AS FOUR PHASE

Clockwise Direction			
Voltage (V)	**Current(A)**	**Time(ms)**	**Speed(rpm)**
10	0.51	30	250
15	0.71	20	375
20	0.91	15	500
Anti-Clockwise Direction			
10	0.48	30	250

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15	0.66	20	375
20	0.88	15	500

TABLE V
EXPERIMENTAL RESULTS WHEN OPERATES AS THREE PHASE

Clockwise Direction			
Voltage (V)	**Current(A)**	**Time(ms)**	**Speed(rpm)**
10	0.34	32	234.37
15	0.63	22	340.87
20	0.83	15	500
Anti-Clockwise Direction			
10	0.34	32	234.37
15	0.60	22	340.87
20	0.81	15	500

V. CONCLUSION

The proposed ten step commutation logic for five phase BLDC motor was developed and established the four quadrant operation of motor.The simulation of proposed commutation algorithm was carried out in MATLAB/SIMULINK and the results are validated with the experimental results. The algorithm provides simple implementation with reduced switching loss. The hall sensor pattern and the corresponding switching sequence at which the rotor rotates are determined and the corresponding waveform ofcurrent through each phase is verified with its simulation result and experimental result.The speed of rotation of motor and its current waveform when motor operates in five phase,four phase and three phase was evaluated and the results of the same with different voltages are presented and thereby the reliability and fault tolerant capability of five phase BLDC motor with ten step commutation logic was validated.

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