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Original Article

Two Structures for Controlling Multiphase BLDC Motors in Fault Mode and High Reliability

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Abstract

In this paper, two different structures of a multiphase inverter for controlling a Brushless DC (BLDC) motor are presented and compared parameters. These two structures are in fault mode. In the first structure, each phase of the BLDC motor is fed from an individual H-Bridge inverter, which is controlled by a Proportional-Resonance (PR) controller. The system dealt with in this paper is designed especially for reliability-critical applications. In other words, the motor structure has to be implemented not to compromise the drive performance even in fault conditions. For these purposes, modular designs to minimize the coupling between each phase. in the second structure, a typical six-legged inverter is used, which is divided into two groups of three phases with double Y-connected windings displaced by 30 degrees is presented and switching is done using Space Vector Pulse Width Modulation (SVPWM). According to the model, the use of SVPWM modulation for a six-phase motor reduces computations. MATLAB/Simulink software has been used to analyze these two structures and the results of its simulations are given.

Keywords: BLDC motor; current control; multiphase; inverter; reliability.

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1. INTRODUCTION

In these days, the usage of permanent magnet motors is greatly increased as the performance of permanent magnet is developed. Because of the characteristic of permanent magnet motor as high efficiency, large output power, the permanent magnet motor is widely used in industrial application, naval application, etc. The permanent magnet motor can achieve large torque at low speed region and the maintenance is easier than other typical machine [1]. Multiphase motor drives possess many advantages over the traditional three-phase motor drives such as reducing the amplitude and increasing the frequency of torque pulsation, reducing the stator current per phase without increasing the voltage per phase, lowering the dc link current harmonics and higher reliability. By increasing the number of phases it is also possible to increase the torque per ampere for the same volume machine [2].

Multi-phase motors are primarily used in a few specific applications such as electric and hybrid vehicles, marine vessels, aerospace systems, and electric locomotives. Although multi-phase inverters require more switching devices than basic three-phase inverters, their design is relatively simple [3].

In this paper, two different inverter structures for a six-phase BLDC motor are compared with the aim of analyzing the torque and operation of the motor in the event that any fault and a number of motor phases are taken out of circuit, and the reliability of the two structures is investigated. These structures are of great value in sensitive applications such as the propulsion motors of ships or submarines where the motor must continue to move in any situation.

The first structure, using six H-bridges inverters, switches the six phases of the motor independently, and uses a PR controller to control the current in each phase. In the second structure, a conventional six-legged inverter is used and switched using SVPWM.

2. CONTROL METHOD AND INVERTER OF THE FIRST STRUCTURE

The structure dealt in this proposal is designed especially for high reliability-critical applications. In other words, motor structure has to be implemented not to compromise the drive performance even in fault conditions. For these purposes, modular designs to minimize the coupling between each phase. It gives electrical isolation of stators and no neutral point exists. Each phase is driven by individual H-bridge

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(single phase) inverters and one has no effect on others when any fault occurs. With these structures, fault tolerance is ensured since healthy phases can continue operation under fault conditions and inverters out of order can be disconnected to be repaired or replaced. The structure of the inverter is visible in Fig. 1.

In this structure, to increase reliability, two independent sources can be used to fed single-phase inverters, so that one group of stator windings is fed from the first source and the second group from another source, in this case, if something happens to the source, the motor will not fail.

2.1. Torque Ripple Reduction

Permanent magnet (PM) machines with trapezoidal back emf have been widely used due to their simplicity in their control. These machines inherently have three types of torque ripple associated with them [4].

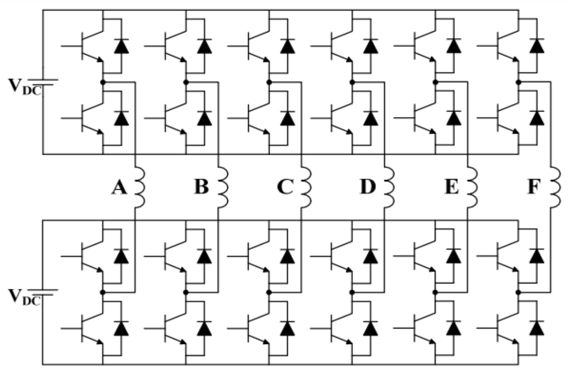


Fig. 1. Inverter of first structure (H-bridge for each phase).

1) The cogging torque due to the interaction of the magnet and the stator tooth

2) The reluctance torque resulting from the interaction of the stator magnetomotive forces (MMF's) with the angular variation of the rotor magnetic reluctance.

3) The ripple due to the commutation of current from one phase to the other.

The achievement of smooth torque production in permanent magnet alternating-current machine drives is a demanding objective that requires painstaking attention to every aspect of machine and controller design. This operation requires the determination of the cogging torque and the commutation torque in order to proceed with further optimization either from the design or the controller aspects. Some careful design leads to low cogging torque. However, the commutation can generate a substantial ripple that has to taken into account to achieve a high performance drive [5]. One of the aspects of torque ripple study is related to the design of motor structure, which was briefly explained. Another aspect of torque ripple reduction is control methods and their use. In this paper, torque ripple study with control methods in fault conditions.

BLDC motors have trapezoidal back EMF waveforms and are generally fed with rectangular stator currents to produce constant torque. Unfortunately, in practice, non-uniformity of magnetic material and design trade-offs make it hard to induce the desired trapezoidal back EMF. Besides, cogging torque from the interaction between the permanent magnets of the rotor and stator slots also causes torque pulsations [6].

PI controlled rectangular phase currents are injected and the torque ripple reduction from the increase of operating phase number. Fundamental components in torque ripple come from the non-ideal trapezoidal back EMF [6].

2.2. Pr Controller

Generally, a three phase BLDC motor with trapezoidal back EMFs is operated by square wave currents to produce constant torque. For the separate winding 6-phase motor dealt in this paper, however, although sinusoidal currents are fed, torque ripple is expected to reduce by compensating each 3 phase groups' ripple components.

Current regulation is an important issue for power electronic converters, and has particular application for high performance motor drives and boost type Pulse Width Modulated (PWM) rectifiers. Over the last few decades considerable research has been done in this area for voltage source inverters, and from this work three major classes of regulator have evolved, i.e., hysteresis regulators, linear PI regulators, and predictive regulators [7]. These classes can be further divided for three phase regulators into stationary and synchronous d–q reference frame implementations by applying ac machine rotating field theory [8, 9].

In general, three phase stationary frame regulators are regarded as being unsatisfactory for ac current regulation since a conventional PI regulator in this reference frame suffers from significant steady-state amplitude and phase errors. In contrast, synchronous frame d–q regulators can achieve zero steady-state error by acting on dc signals in the rotating reference frame, and are therefore usually considered to be superior to stationary frame regulators. However, a synchronous frame regulator is more complex, as it requires a means of transforming a measured stationary frame ac current (or error) to rotating frame dc quantities, and transforming the resultant control action back to the stationary frame for execution [10].

To apply sinusoidal currents without phase delay or steady state errors, synchronous frame PI controllers are commonly employed. However, as this system consists of 6 single phases fed by 6 H-bridge inverters, synchronous frame controllers are difficult to implement. Accordingly, stationary reference controllers equivalent to synchronous frame ones have to be used [10] and it is called PR (Proportional and Resonant) controller. The transfer function of PR controller is given in (1) and it is applied to all 6 single phases.

$$G_{DC}(S) = k_P + \frac{k_I}{S} \qquad G_{AC}(S) = k_P + \frac{2k_I S}{S^2 + \omega_0^2} \qquad (1)$$

Equations (1) The ideal state is the PR controller transfer function, which another expression must be added for the damping coefficient to implement Equation (2).

$$G_{AC}(S) = k_P + \frac{2k_I \omega_c S}{S^2 + 2\omega_c S + \omega_0^2} \qquad (2)$$

ω_c the cut-off frequency or operating frequency is to be set, typically a number between 5 and 15 radians per second placed. You can see the corresponding block diagram in Fig. 2. To remove the harmonic from the current and reach the sinusoidal waveform of the current, for the desired harmonics that need to be removed, the pr block is paralleled and the corresponding harmonic frequency is placed in it. By adjusting the resonance coefficients, the amount of harmonic attenuation can be controlled.

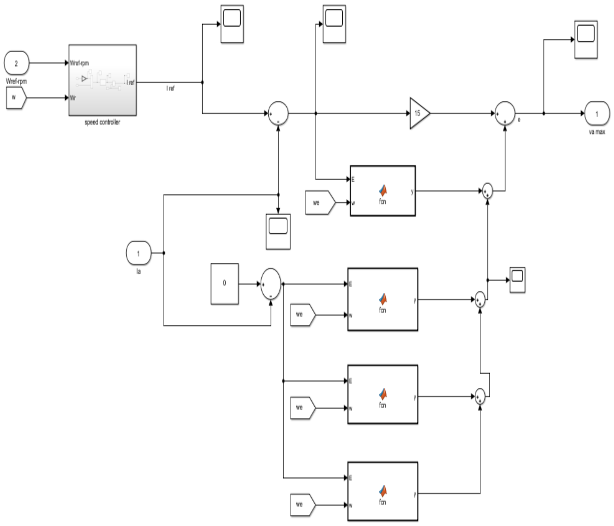


Fig. 2. Structure of current controller

3. MODULATION AND STRACTURE OF SECOND INVERTER

Dual three-phase BLDC has two sets of three-phase stator windings spatially phase shifted by 30 electrical degrees, as shown in Fig. 3. It is also named as six-phase motor, split-phase motor or double-star motor. The motor usually has isolated neutrals and is supplied by a six-phase inverter (Fig. 3). With the increase of phase number, the power can be divided into more inverter legs. The cost price for power electronic components in this structure is more economical than the previous structure, because fewer elements are used in this structure.

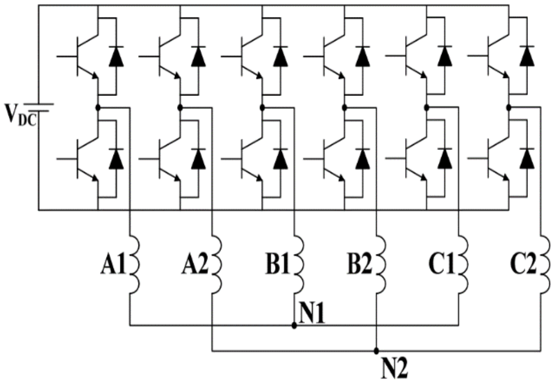


Fig. 3. Inverter of second structure.

The dual three-phase motor is suitable for low voltage and large power applications, such as ship propulsion and electrical vehicles. With the special winding structure, the dual three-phase motor can eliminate sixth harmonic torque propulsion which always exists in three phase motor. Another advantage is the high reliability. The motor can still run normally with proper control strategy when losing one or more phases [11]. Space vector pulse width modulation (SVPWM) is a more advanced technique for generating sine waves and provides a high voltage with less THD for the motor. The main goal of any modulation technique is to obtain variable output with maximum principal component and minimum harmonics. Space vector modulation method is the best technique for using variable frequency drive. To improve the DC bus voltage utilization, the on-off states of the upper and lower switches in an inverter leg are complementary. Thus, there are $2^6 = 64$ switching states in the six-phase two-level inverter. The 64 switching states correspond to 64 winding phase voltages, which can be represented by 64 column matrices. In the non-fault-tolerant SVPWM, the 64 column matrices are mapped to three decoupling planes by using a six-dimensional orthogonal matrix, and 64 basic voltage vectors are obtained as V_0–V_{63}. In this paper, the conventional method is not used to implement SVPWM modulation, because the conventional method for multiphase motors, such as our motor, has a large number of voltage vectors and prolongs the calculations. To simplify the implementation of this modulation by using another method, we have reduced the volume of these calculations.

Selecting the appropriate switching state vectors and computing their on-durations will become straightforward provided that the six-phase inverter is divided into two independently switched three-phase inverters with a common dc link voltage. In this technique, the switching state vectors are mapped into the inverter basis frame rather than the machine basis frame. Therefore, the goal of the space vector PWM control is to synthesize two reference voltage vectors having the same magnitude but phase shifted by 30'. the switching state vectors of one modulator are rotated 30' clockwise, and the same reference vector is applied to both modulators that shown in Fig. 4 [12].

4. SIMULATION RESULTS

The parameters of the simulated BLDC motor are the same for both structures and are given in Table 1. The torque is assumed to be 10 N.m.

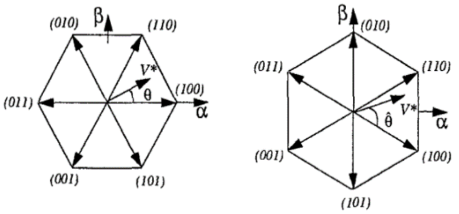


Fig. 4. The switching state vectors are rotated by 30 degree clockwise (second approach)

Table 1. Parameters

Parameters	***Values***
Moment of inertia	0.008 kg.m^2
Friction coefficient	0.001 N.m.s/rad
Rotor magnetic flux	0.175 Wb
Stator resistance	2.875 Ω
Statotr inductance	8.5 mH
Number of pole	4
DC source voltage	500 V

In the first structure, as mentioned in the previous sections and in the [5], the current waveform without a controller is the same as Fig. 5, (In the first moment, the motor is without load and in 0.25 seconds, a load is applied on the motor) which has harmonics, and its harmonics can also be seen in Fig. 6. According to Fig. 6, the 5th and 7th harmonics have the highest value. The horizontal axis is harmonic order and the vertical axis is the ratio of the desired harmonic magnitude to the fundamental harmonic.

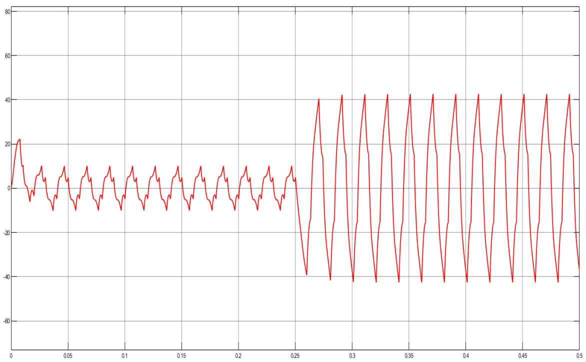


Fig. 5. Current waveform without a controller.

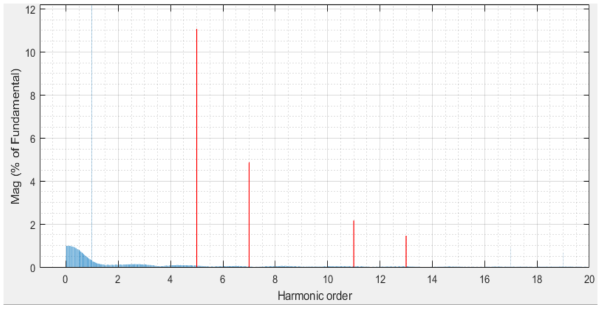


Fig. 6. Harmonics analysis of current waveform without a controller

Using the pr controller, the 5th and 7th harmonics are attenuated in the current, and a more suitable sinusoidal waveform is obtained for better motor performance. According to Fig. 7 and Fig. 8, the current and its harmonics can be seen that the desired harmonic has decreased.

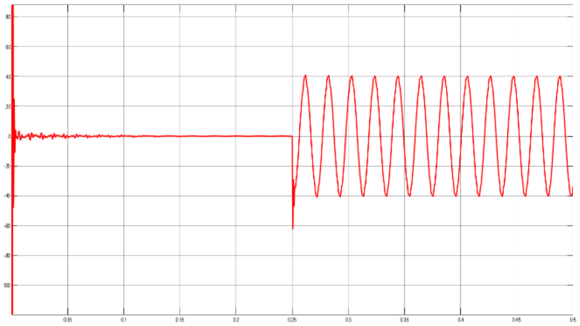


Fig. 7. Current waveform with PR controller

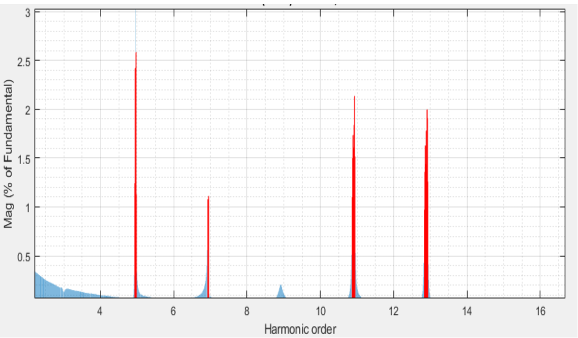


Fig. 8. Harmonics analysis of current waveform with PR controller

In the second structure, where the six-phase system is divided into two groups of three phases and switched using SVPWM, the current waveform of one of its phases can be seen for sample in Fig. 9.

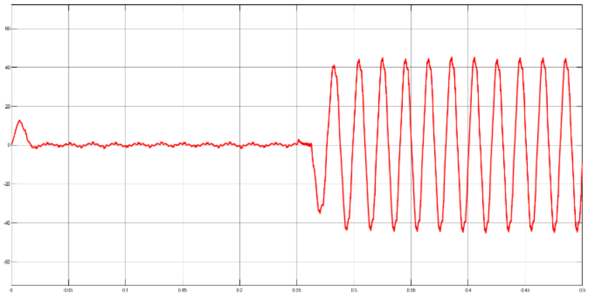
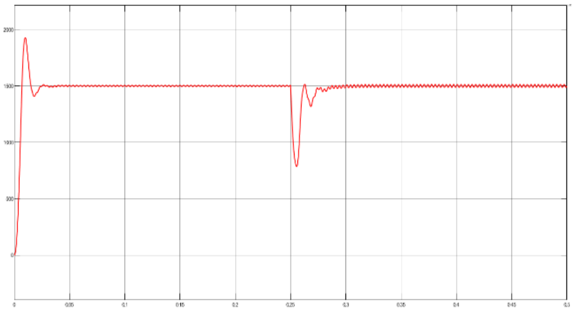
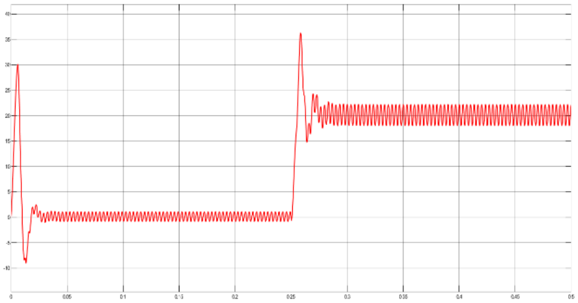


Fig. 9. Current waveform of second structure

By implementing the control method, speed and torque ripple in a healthy and normal operation of the motor is reduced. Figure 10 show the motor speed and torque without controller. Fig. 11 show the motor speed and torque when the PR controller is applied.

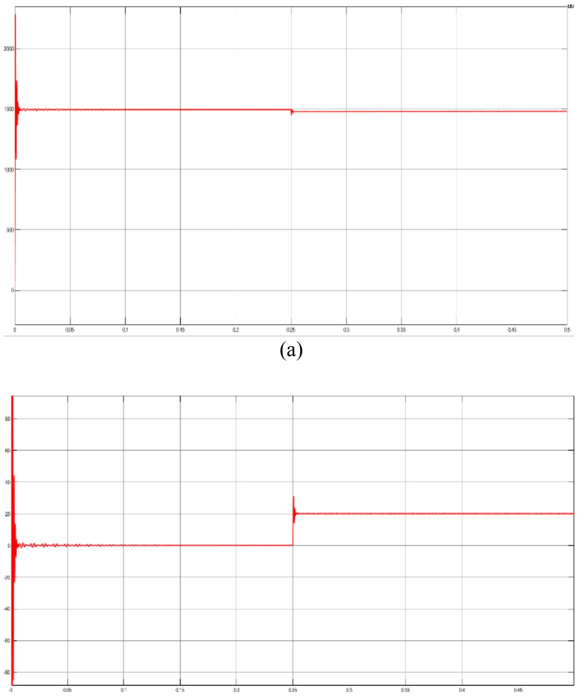


(a)



(b)

Fig. 10. First structure without controller: (a) Speed. (b) Torque



(a)

(b)

Fig. 11. First structure with PR controller: (a) Speed. (b) Torque

In the first structure, where each phase is independent of the other and is switched using an H-bridge inverter, if an fault occurs, we can disconnect up to four of the six phases of the motor and the motor will continue to operate. Obviously, with the exit of each phase, the torque ripple will increase and the motor power will decrease, but it has acceptable torque for sensitive conditions. Fig. 12 shows the output torque of the motor while one phase of the motor is output every half second, so at 2.5 seconds the motor becomes unstable and then stops. In the second structure, which is switched by a conventional six-legged inverter, if an fault occurs and we have to take one phase out, the other phases of that three-phase group must also be taken out of circuit because the motor is unbalanced and the produces too much torque ripple. And the motor must continue to move with its other healthy three-phase group (Fig. 13).

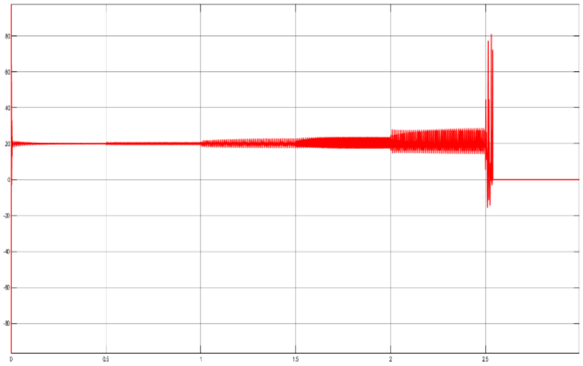


Fig. 12. Torque of the first structure in fault mode

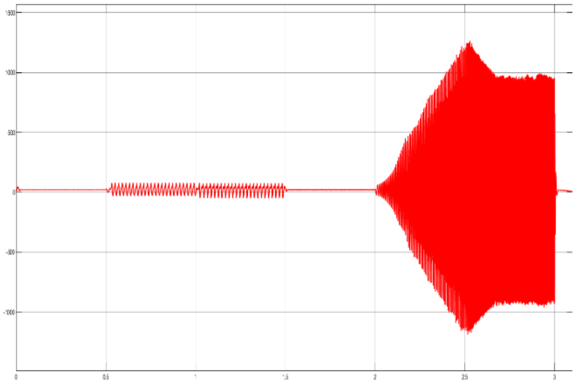


Fig. 13. Torque of the second structure in fault mode

5. CONCLUSION

Today, the speed of use of BLDC motors has greatly increased and they are used in various applications. Reducing torque and speed fluctuations is very important in using this engine. Due to the superior characteristics of three-phase BLDC motors compared to conventional AC and DC motors, but for use in sensitive applications such as military, aerospace and electric vehicles need further study and research and thus improve the performance characteristics of this The model is made of motors. Multiphase BLDC motors have received a lot of attention in the mentioned applications due to their advantages. Due to the importance of multi-phase BLDC motors, in this paper we examined and compared the two drive structures for a six-phase BLDC motor under normal operating conditions and fault and their reliability. First, we tested a six-phase BLDC motor without a controller, and then we implemented a PR controller, which is also the main drive structure of this paper, and we saw a reduction in torque fluctuations in normal and fault mode. In the second structure, switching was performed using SVPWM modulation, which also improved speed and torque fluctuations. By comparing the first and second structures, the structure of the first drive in normal and fault conditions showed the best performance and has the least oscillations of speed and torque, and at the same time showed good performance for practical implementation can be Implemented and executed the relevant controller code in microcontrollers with a small and relatively simple complexity. In general, both structures performed well to improve uninterrupted performance against phase fault.

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