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Failure study on Increased Number of Phases for the Optimum Design of BLDC Motor

Kiran George
Department of Electrical Engineering
M A College of Engineering, Kothamangalam

Shinoy K. S.
Sci. /Engr.
VSSC, Trivandrum

Sija Gopinathan
Associate Professor
Department of Electrical Engineering
M A College of Engineering, Kothamangalam

Abstract— **Fault-tolerant capability of electrical motor drives is an essential feature in applications such as automotive, aeronautic, and many others. A multi-phase permanent-magnet (PM) motor exhibits a high fault tolerant capability, as it can be designed to reduce the fault occurrence as well as to operate indefinitely in the presence of fault. With multi independent phases, in the event of failure of one or more, the remaining healthy phases let the motor to operate properly. This paper deals with the analysis of the behavior of a multi-phase motor in case of some common faults, as open circuit of either one or two or three phases**.

***Index Terms*— multi-phase, fault tolerant, Permanent-magnet motor**

I. Introduction

In opposition to classical three-phase machines, multiphase machines are well suited for high-reliability drives, since the increase of the number of phases reduces the power per phase [1,4], and allows them to operate with the loss of feeding of one phase without any change in the power electronics and control architecture. Electromechanical Actuators (EMAs) take more space in aircraft day by day. From secondary applications (i.e. stairs, door actuation, door locking device, etc.) EMAs start to be adopted in more significant applications as brakes, spoiler or flap actuation moving with many R&D programs to primary aircraft application. The More Electric aircraft (MEA) concept intends the wider adoption of electrical systems in preference to established hydraulic and pneumatic systems. Possible important improvements in machines and drives for the MEA applications can be obtained by introducing multi-phase machines fed by multi-phase power electronic converters, where both the motor and drive design must satisfy severe fault-tolerant requirements. In facts, EMAs for aerospace applications must assure the maximum reliability and safe operation even in the occurrence of fault conditions until maintenance is possible [5,7]. The design foresees higher phase number to increase reliability and performance. Clearly, the increase of number of phases must be balanced against the increasing complexity of a high phase number and the inevitably greater chance of a failure. About the faulty mode operation, the following conditions have been investigated:

A) one phase open;
B) two phases open;
C) three phases open

When one, two or three phases are open, due to a device failure or a fault in the phase windings, a new set of currents for the healthy phases should be imposed in order to satisfy the torque values. This paper deals with the analysis of the behavior of five and seven phase motor and results for nine, eleven and thirteen phases, in case of some common faults, as open circuit of either one or two or three phases (the latter being either adjacent or not).

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II. MOTOR DESIGN EQUATION

The EMF contributing to the electromagnetic power is:

$$E = (N_{ph} - 1)2\pi N_t k_w \alpha D_r L B_g n \quad (1)$$

where L is the active motor length, D_r is the rotor outer diameter, N_{ph} is the number of phases, N_{ph}-1 is the number of phases conducting simultaneously, N_t the number of turns per phase, k_w is the winding factor, B_g the air-gap magnetic flux density and n the rotational speed in rev/s.

The electromagnetic torque is:

$$T = (N_{ph} - 1)N_t k_w \alpha D_r L B_g i \quad (2)$$

where, i is the square-wave current amplitude[8,9].

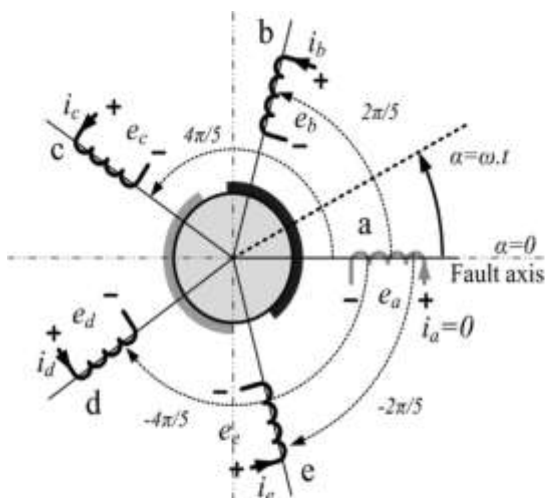

Fig. 1. *N-phase* PM motor.

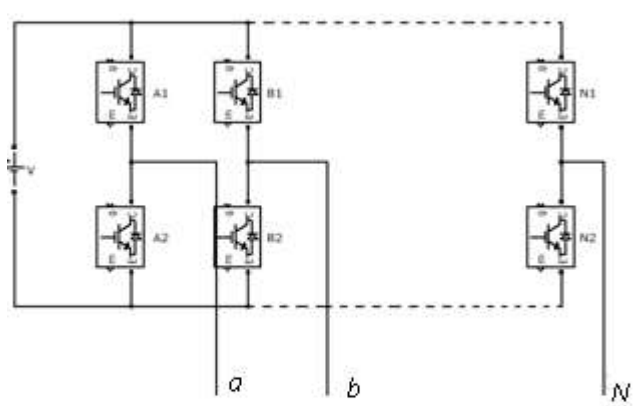

Fig. 2. *n*-phase power converter

The electromagnetic power (P_0) and torque are always positive because negative EMF times with negative current feeding gives a positive product. Here we can see that as the number of phases increases the torque and emf increases by a factor N_{ph}-1.

We have

$$P = T\omega \quad (3)$$

and $P = \sum EI \quad (4)$

Therefore $T \alpha E \quad (5)$

Hence the effect of increased number of phases can be studied from the voltage equations.

III. MULTI-PHASE DRIVE TOPOLOGY

Consider an *n*-phase two-pole PM machine, as shown in fig. 1, where phase 1 is under fault condition. The polarities of the back EMFs, induced in the stator windings, and the direction of the excitation currents are also shown in this figure. This helps in understanding the case where N_{ph}-1 phase are conducting simultaneously. The rotor angular speed is ω.

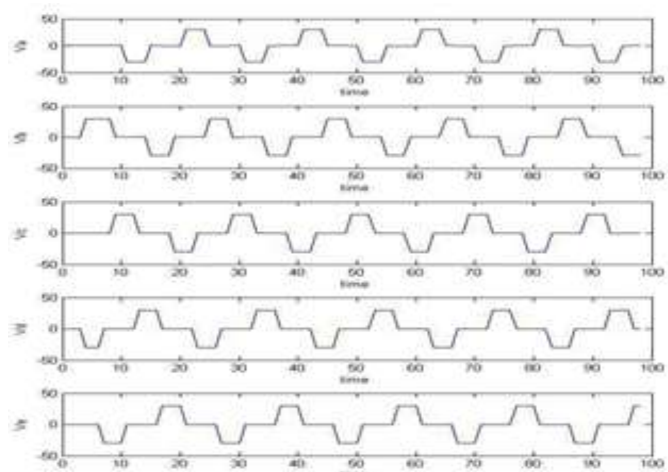

Fig. 3.five –phase voltage wave form

Open-circuit in a power switch causes asymmetric feeding of motor phase by the healthy leg of H-Bridge. This condition needs rapid detection and turning off of all the power switches of the faulty module. The topology we use here is H-bridge inverter topology with number of legs equal to the number of phases shown in fig.2. The constant torque is generated by

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feeding the motor phases with constant current in constant back-EMF wave region as expressed in (2). The five-phase voltage wave form obtained is shown in fig.3.

IV. ANALYSIS ON FIVE AND SEVEN PHASE TOPOLOGIES

The analysis is done for the study of various fault condition of different phase during a time period. In order to study the effects of the faults we have considered the five phase voltage equation. The conduction period for a three-phase machine is 120˚,where as it is 144˚ for a five-phase machine and for a seven phase machine it is 155°. Therefore to deliver the same energy in each revolution, the three-phase generator has to deliver larger magnitude pulses of energy leading to higher torque ripple at the shaft and with a lower mechanical frequency hence greater vibrations and fatigue stress. Improvements in torque ripple provided by the multi-phase machine are important features of renewable energy generation systems, where vibration and fatigue offer significant challenges to the industry. By giving a proper control algorithm it is possible for a multi-phase machine to provide a constant torque. The five phase voltage equation is given by,

$$E_a = Esin\omega t \quad (6)$$

$$E_b = Esin\left(\omega t - \frac{2\pi}{5}\right) \quad (7)$$

$$E_c = Esin\left(\omega t - \frac{4\pi}{5}\right) \quad (8)$$

$$E_d = Esin\left(\omega t + \frac{4\pi}{5}\right) \quad (9)$$

$$E_e = Esin\left(\omega t + \frac{2\pi}{5}\right) \quad (10)$$

Considering the period $-\frac{\pi}{10}$ to $\frac{\pi}{10}$ that is for duration of 36° the active phases contributing to the electromagnetic torque is *b*- phase *c*-phase *d*-phase and *e*- phase. The fig.4 shows the effect of commutating the back EMF waveforms of all the five phases with a square wave drive. The commutations occur every 36°during which a square wave drive would force a constant current against the back-EMF. With constant current drive the resulting torque wave form would follow the shape of the back-EMF waveform, and therefore this figure gives an idea of the inherent electromagnetic torque ripple that would be expected with square wave drive and perfect commutation of the phases [10]. The importance of the back-EMF wave shape for minimum torque ripple with square wave drive is clearly seen. For a five phase system the output dc voltage has a fundamental frequency of 10 times the input frequency and that in a seven phase is 14 times the fundamental frequency and which was 6 times in three phase system. The average EMF for a five phase can be found out by,

$$E_{avg} = \int_{-\frac{\pi}{10}}^{\frac{\pi}{10}} Esin\left(\omega t - \frac{2\pi}{5}\right) + sin\left(\omega t - \frac{4\pi}{5}\right) + Esin\left(\omega t + \frac{4\pi}{5}\right) + Esin\left(\omega t + \frac{2\pi}{5}\right) \quad (11)$$

The amplitude of the wave obtained is a factor that contributes to the total torque produced as per (5).Hence it is necessary to study the effect of fault of each phases on the net torque produced in order to make a proper design of the machinery and to provide a proper control circuitry .

The feasible fault conditions in phase windings of a five-phase machine and seven phase machine under analysis can be categorized in the following five groups:

A) Single-phase
B) Non-adjacent double-phase
C) Adjacent double-phase
D) Non-adjacent triple-phase
E) Adjacent triple-phase

A) Single-Phase Open-Circuit Fault

The key advantage of multiphase machines is that it can operate even when N_{ph}-2 phases gets faulty. Under the operating condition mentioned above if for a five phase machine, the phase B gets faulty due to open circuit, there is a considerable reduction in torque produced. This reduction can be overcome by providing an appropriate control circuit to keep the torque constant. The average EMF contributing to the electromagnetic torque for a five phase is given by,

$$E_{avg} = \int_{-\frac{\pi}{10}}^{\frac{\pi}{10}} sin\left(\omega t - \frac{4\pi}{5}\right) + Esin\left(\omega t + \frac{4\pi}{5}\right) + Esin\omega t+2\pi 5 \quad (12)$$

B) Non-Adjacent Double-Phase Fault

The choice of the faulty phases is completely arbitrary;

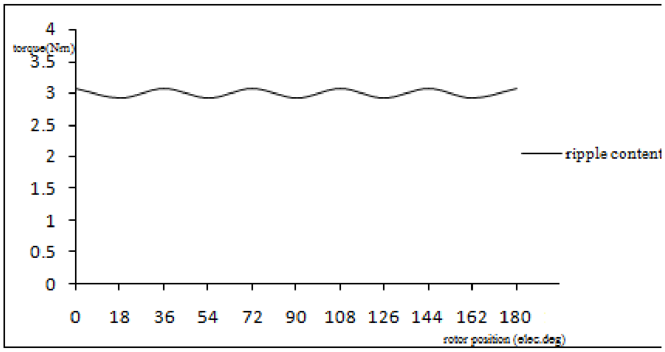

Fig.4 Factor which contributes to torque in a five phase machine

however, to simplify the mathematical notation *c*-phase and *e*-phase are chosen in this case. The analysis is done for both five phase and seven phase and the average EMF contributing
to the torque is computed. Considering the same period of operation of the motor, for the two non-adjacent phases *c*-phase and *e*-phase under fault the average EMF is computed by (13).

$$E_{avg} = \int_{-\frac{\pi}{10}}^{\frac{\pi}{10}} sin\left(\omega t - \frac{4\pi}{5}\right) + Esin\left(\omega t + \frac{2\pi}{5}\right) \quad (13)$$

C) Adjacent Double-Phase

The two adjacent phases we have considered for the analysis are *b*-phase and *c*-phase. Again we can see that the fundamental component contributing to the torque has been reduced. The average EMF contributing to torque in this case is given by (14). For a five phase machine in the considered time period as per the current situation it is not possible to tolerate a fault in three phases. Hence it is necessary to force the a-phase operating in this interval.

$$E_{avg} = \int_{-\frac{\pi}{10}}^{\frac{\pi}{10}} Esin\left(\omega t + \frac{4\pi}{5}\right) + Esin\left(\omega t + \frac{2\pi}{5}\right) \quad (14)$$

D) Non-Adjacent Triple-Phase

In this case for the analysis purpose we have chosen arbitrarily are *b*-phase, *d*-phase, *e*-phase. Here as already mentioned it is seen that *a*-phase is forced to operate so that more reliability can be obtained for the multiphase system. The average EMF contributing to the torque is given by (15).

$$E_{avg} = \int_{-\frac{\pi}{10}}^{\frac{\pi}{10}} Esin\omega t + sin\left(\omega t - \frac{4\pi}{5}\right) \quad (15)$$

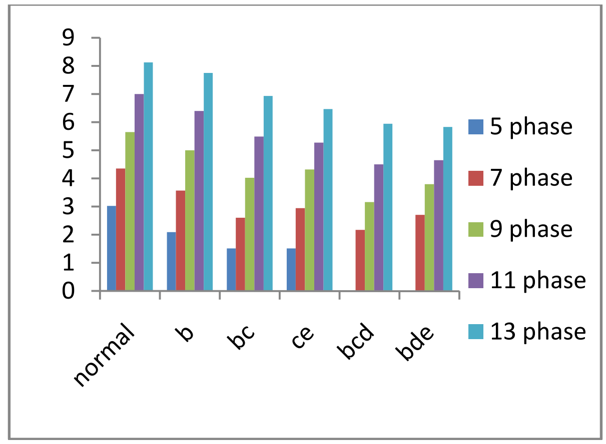

Fig.5 average EMF contributing to the torque by different number of phases under different fault conditions

E) Adjacent Triple-Phase

The three adjacent phases considered are *b*-phase, *c*-phase, *d*-phase. The average EMF contributing to the torque is given by (16). For higher number of phases more faults can be tolerated. TABLE I gives the factor contributing to the output, for different operating conditions.

$$E_{avg} = \int_{-\frac{\pi}{10}}^{\frac{\pi}{10}} Esin\omega t + Esin\left(\omega t + \frac{2\pi}{5}\right) \quad (16)$$

V. ANALYTICAL RESULTS AND FUTURE SCOPE

Numerical analysis is done for different number of phases and the values obtained are shown in a comparing manner as shown in fig.5, shows the average EMF, as a factor which contributes to the torque in the motor. In future it is beneficial to consider this factor so as to optimize the design of the machine for better performance and reliability

Hence as a result of the analysis, the torque and EMF equations can be modified replacing the factor N_{ph}-1 by the average of the EMF which actually the component is contributing to the output power.

VI. CONCLUSION

This paper shows the advantage of multiphase together with the enhancement in the torque by using multiphase. The paper gives the actual factor which contributes to the output regardless to the theoretical approach. This helps in developing a more reliable design of a machine.

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