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Multi-phase induction machine drive research—a survey

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Abstract

Due to the potential benefits resulting from the use of a phase order higher than three in transmission, some interest has also grown in the area of multi-phase machine. For machine drive applications, multi-phase system could potentially meet the demand for high power electric drive systems, which are both rugged and energy-efficient. High phase number drives possess several advantages over conventional three-phase drives such as: reducing the amplitude and increasing the frequency of torque pulsation, reducing the rotor harmonic currents, reducing the current per phase without increasing the voltage per phase, lowering the dc link current harmonics, higher reliability and increased power in the same frame. The high phase order drive is likely to remain limited to specialized applications where high reliability is demanded such as electric/hybrid vehicles, aerospace applications, ship propulsion, and high power application where a combination of several solid state devices form one leg of the drive. The research has been underway for the last two decades to investigate the various issues related to the use of multi-phase machine as a potential alternative to the conventional three-phase machine. This paper, therefore, reviews the progress made in multi-phase induction machine drive research and development since its inception. Attempts are made to highlight the current and future issues involved for the development of multi-phase induction machine drive technology for future application.

Keywords: Analysis; Drive; Induction motor; Multi-phase; Modeling; Stability

1. Introduction

High power electric machine drive systems have found many applications such as pumps, fans, compressors, rolling mills, cement mills, mine hoists, to name a few. At present, the most successful type of high power drive systems is cycloconverter-fed electric machine drives and synchronous machines fed by current source thyristor inverters. Voltage source inverters, despite their advantage of being able to use low cost induction machines, are still limited to the lower end of the high power range due to the limitations on gate-turn-off type semiconductor power device ratings.

In the past decades, multi-level inverter fed electric machine drive systems have emerged as a promising tool in achieving high power ratings with voltage limited devices. The typical structure of such systems is the three-level inverter three-phase electric machine system [1]. A three-level voltage source inverter is a series switch type structure, which operates with split-voltage dc bus. The voltage stress on each device is only half of the total dc bus voltage and, thus, a doubled dc bus voltage can be achieved. The parallel circuit dual to the multilevel system is essentially the multi-phase inverter fed electric machine drive system. In a multi-phase machine drive system, more than three-phase windings are housed in the same stator of the electric machine, and the current per phase in the machine is, thereby reduced. In the most common of such structures, two sets of three-phase windings are spatially phase shifted by 30° electrical. In such systems, each set of the three-phase stator winding is excited by a three-phase inverter, therefore, total power rating of the system is theoretically doubled. In addition to enhancing power

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rating, it is also believed that drive systems with such multi-phase redundant structure will improve the reliability at the system level [2–6]. In particular, unlike in normal three-phase system, the loss of one phase in multi-phase machine drive system does not prevent the machine from starting and running. This paper deals with a state-of-the-art discussion of multi-phase induction machine drive research and development, highlighting the analytical and technical considerations as well as various issues addressed in the literature towards practical realization of this new technology.

2. Concept and benefits

2.1. Concept and feasibility studies

Ward and Harer [7], for first time in 1969 have presented the preliminary investigation of an inverter-fed five-phase induction motor and suggested that the amplitude of torque pulsation can be reduced by increasing the number of stator phases. A very few examples of multi-phase induction motors can be found in the literature. Nelson and Krause [8] carried out computer simulation on three types of six-phase motors using an inverter source. They found that by using a motor with 30° phase belts, the sixth harmonic torque pulsation usually encountered in inverter driven three-phase motors was eliminated, though the peak stator currents were increased. Danzer has reported the test results on five-phase motors [9–11]. The reason given for using five phases was to reduce the current such that it would match the rating of the available thyristors, for inverter source. However, the third harmonic current was found to be excessive when it was supplied by the inverter. Motors with many phases have been proposed for high degree of reliability. These few attempts to develop multi-phase induction motors show that they have some advantages over conventional three-phase induction motors.

2.2. Benefits

The potential benefits of a multi-phase induction motor result from the 30° displacement angle between the two three-phase sets of a six-phase motor, leading to elimination of all the air gap flux harmonics of the order ($6m \pm 1$, $m = 1, 3, 5\ldots$). Consequently, all rotor copper losses produced by these harmonics as well as all the torque harmonics of the order ($6m$, $m = 1, 3, 5\ldots$) are eliminated. The most significant advantages include: capability to start and run even on one or two of its many stator phases open or short circuited, lower current per phase without an increase in voltage per phase, lower dc link current harmonics, higher reliability and increased power in the same frame.

3. Method of analysis

The analysis of standard symmetrical multi-phase (more than three phases) induction machines is presented in several texts [12]. That, however, cannot be directly applied to the machines with unsymmetrical phase displacements between the multiple winding sets. The derivation of the voltage equations in phase variables and the transformation to the $d–q–o$ reference frame of a multi-phase machine with unsymmetrical phase displacement has been reported by Nelson and Krause [8]. Analysis of six-phase machine with 0° phase displacement between two winding sets has been given by Singh et al. [13]. Abbas [14] and Lipo [15–17] have reported a model for inverter fed dual three-phase (spatially phase shifted by 30° electrical) induction machine drive system. The most commonly used analytical tool for the analysis of unbalanced operation of electric machines has been the well-known symmetrical component method. In this method, a balanced structure is assumed after the machine loses one or more of its phases. Although it has been used successfully in the steady-state analysis of sinusoidal excitation, however, as far as the dynamics of machine is concerned, the method loses its utility due to the fact that the interaction between the lost phases and remainder of the machine windings no longer exists and this drastically alters the dynamic behavior of the machine. Two separate models have been used by Zhao et.al. [16,17] to analyze the dynamic behavior of machines for balanced, and unbalanced excitation due to open circuit. These models are silent about the analysis of unbalanced condition caused by the short circuit at stator terminals. The two-axis ($d–q$) model of the multi-phase machine in an arbitrary reference frame was developed by the present author [5,6] and a detailed analysis of the machine under balanced, and unbalanced (open circuit and short circuit both) operating condition has been carried out. In this model, the effect of mutual leakage reactance between the two stator winding sets have also been included and is valid for any angle of displacement between the two three-phase winding sets.

4. Description of general nomenclature

A machine can have as many phases as coils per pole pair. The number of phases for a machine is assumed to be the same as number of stator terminals or leads, excluding neutral. However, giving the number of phases is not always an adequate description because two machine versions are possible based on two possible values of the phase belt angle for a given