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. © 2002 Elsevier Science B.V. All rights reserved.

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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 $30^\circ$ 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
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...
number of phases. Almost all the three-phase machines have 60° phase belts but sometimes these machines are wound with 120° phase belts, and have some different characteristics from 60° versions [18,19]. Table 1a and b include the names and relate them to the phase belt angle and the minimum number of stator leads required [19].

5. Winding layouts

A six-phase machine can easily be constructed by ‘splitting’ the 60° phase belt into two portions each spanning 30° [8]. This technique is illustrated in Table 2 for a simple machine having six poles and thirty-six slots. The winding distribution factor increases from 0.965 for three-phase to 1.0 for six-phase for the split phase belt connection. A ‘true’ six-phase distribution that retains the same winding pitch and distribution factor [15] is shown in Table 2. However, due to the extra coil side insulation required, this ‘true’ six-phase distribution is generally less desirable than the split phase belt connection [15].

6. Space harmonics in multi-phase machine

The air gap distribution in cylindrical rotor machines contains undesirable harmonics, and among these are the phase belt harmonics. These as well as slot harmonics, produce cusps and dips in the torque curve for slip near unity. They contribute to leakage reactance and stray load loss. Stator coil pitch is normally chosen so as to reduce lower order phase belt harmonics, which are generally the largest. The phase belt harmonics that can exist in the spatial distribution of flux are those, for which, the harmonic order number $k$ satisfies the equation:

$$k = 2qi \pm 1$$  \hspace{1cm} (6.1)

where, $i$ is any integer.

The lowest order space harmonics are found by using Eq. (6.1). When more phases are used, the order number for lowest harmonics is higher. For example, semi 12-phase machine can have no space harmonics below the 11th. Therefore, the stator coil pitch need not be chosen to reduce the fifth or seventh harmonics, as is generally necessary for three-phase machines. This pos-
Table 2
Winding distribution

| Slot number | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 |
|-------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Phase       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| For 3-phase, 5/6 pitch, 6-pole, 36-slot machine | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  |
| Phase (top layer) | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  |
| Distribution (bottom layer) | x  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  |
| True Six-Phase Winding Distribution for 6-Pole, 36-slot machine | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  |
| Phase (top layer) | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  | b  | a  |
| Distribution (bottom layer) | x  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  | z  | y  | a  | x  | z  |
sibility of eliminating lower order harmonic is a clear advantage of multi-phase machine. Klingshirn, in his paper [19] has presented a detailed study about these harmonics.

7. Equivalent circuit representations

Based on the equivalent circuit of a three winding transformer, the equivalent circuit of the multi-phase (six-phase) induction machine having a double stator winding can be realized as shown in Fig. 1 [15]. The common mutual leakage reactance, $x_{lm}$, in the figure represents the fact that the two sets of three-phase stator windings occupy the same slots and are, therefore, mutually coupled by a component of leakage flux. Note that although the circuit is termed ‘per phase’, in reality the circuit is drawn with two stator circuits, one per three-phase group. The equivalent circuit based on the generalized mathematical model developed by Singh and Pant [5,6] is shown in Fig. 2. The coil pitch affects the leakage reactance of the stator winding. Lipo [15,18,20] has explained this in detail and has given the technique for finding slot reactance. Standard test procedures [21] are available to determine the various machine parameters.

8. Multi-phase induction machine in a phase-redundant drive system

8.1. Phase-redundant drive system

Based on the general concept of parallel redundancy [22,23], the phase redundancy technique [2] relies on inherent capability of a general $n$-phase ac motor to continue operation with $(n−1)$ or less of its many stator phases excited. Thorough evaluation of merits of this technique demands that the number of motor stator phases, $n$ must be more than conventional three and an ac machine potentially has as many phases as coils per pole pair which is almost always greater than three. Thus, the existing ac motors pose no problem for the designers; existing coils are gathered into $n$-phase configuration for $n$ other than three at minimum additional expenses. Fig. 3 is the proposed drive configuration [6] in which, each of the $n$-stator phases is either excited by an independent single phase drive unit or in a group of three (each displaced at 120°) by multiple independent three-phase drive units with possible operational independence to minimize the physical fault propagation from one unit to others.

8.2. Fault analysis

Fault studies form an important step in the design of adequate protective schemes for drive system. The various type of faults that can occur increases with the increase in number of phase. The type of supply system and the impedance across the unexcited winding terminals are the two parameters, which together determine the basic drive configuration during fault. With regard of type of source, the designer is left with a choice between voltage and current source excitation. Since each drive unit in a phase redundant system is provided with as much operational independence as possible to prevent the risk of physical fault propagation from one unit to its neighbor, the basic drive configuration is reduced to four discrete cases as follows:

(i) Voltage source excitation and the short circuit occurring at the input stator phase terminal (VS-SC);
(ii) Voltage source excitation and an open circuit occurring at input stator phase terminal (VS-OC);
(iii) Current source excitation and short circuit occurring at input stator phase terminals (CS-SC);
(iv) Current source excitation and open circuit occurring at input stator phase terminal (CS-OC).

A detailed analysis of the machine under unbalanced (caused by open circuit or short circuit) operating condition have been carried out to study the steady state, transient and dynamic behavior of the machine with different winding configuration (0, 30, and 60° displac-
Fig. 3. Basic n-phase induction machine drive configuration using n-modular H-bridge PWM inverter.

9. Stability analysis

It was recognized first by Rogers [26] that an induction machine operating quite satisfactorily at normal speed might display an oscillatory response that is frequency dependent. The analysis was based on root locus technique. Fallside and Wortley [27] have also analyzed the instability of the induction motor fed by variable frequency inverter, neglecting the effect of harmonics. The effect of machine parameters on the stability of the system was also reported.

Lipo and Krause [28] have performed the stability study of a rectifier-inverter induction motor drive system neglecting stator voltage harmonics and using Nyquist stability criterion. Cornell and Lipo [29] have used transfer function techniques for the development of controlled current induction motor drives and study its stability. MacDonald et al. [30] have developed a linearized small signal model of the current source inverter–induction motor drive to study the stability of the drive and provide a transfer function for different control strategies. Tan et al. [31] have calculated the eigenvalues of double-cage induction motor using decoupled boundary layer model.

In these works, only the fundamental component of the inverter voltage has been taken into account neglecting the effect of harmonics. There is much evidence...
in the historic literature [32–35] dealing with the transient analysis that the transient behavior predicted using the conventional linearized model, although agrees qualitatively, deviates from the actual quantitatively. The cause of deviation may be due to the assumption made in neglecting saturation effect, skin effect, iron losses and mechanical damping etc. However, the saturation effect has been suspected as a prime cause for the disparity between the analytical and experimental results. Some schemes [36,37] have included the saturation effect in the induction motor fed by variable frequency source. These models are adaptive to digital simulation and time domain analysis and successfully predict the instability region precisely. Ahmed et al. [38] has analyzed the stability of linear time invariant systems based on the Liapunov’s first method using the placement of eigenvalues.

The stability studies have thus been carried out in detail for three-phase machine. However, no such study has been carried out for multi-phase (more than three phase) induction machine, to the best knowledge of the authors. A linearized model for 6-phase machine in d−q variables of the machine in synchronously rotating reference frame were developed by the present authors on the lines of the three phase model developed by Krause [39] and Hancock [40]. The resulting machine model is of seventh order. The eigenvalues under different operating conditions were calculated and analyzed. The correlations between different machine parameters and pairs of eigenvalues have been established. The stability of the machine under perturbation of any one variable was examined at a time from the placement of the eigenvalues of the machine. The system is said to be stable if all the eigenvalues are located on the left half of the plane [25].

10. Performance analysis of multi-phase induction machine

The characteristics of several high phase order induction motors were examined by Klingshirn [41]. A detailed performance analysis (no-load and load test) of the six-phase induction machine have been presented by Singh et al. [4,42]. This include the efficiency, power factor, current, magnetization and no-load loss curve. In another study, analytical and test results on a scheme for power factor correction of an induction machine using an auxiliary stator winding in conjunction with a PWM voltage inverter and a single capacitor on dc side have been presented by Tamrakar and Malik [43]. In this study a criterion has been developed to select the optimum value of the power factor for best performance of the PWM inverter-fed induction motor drives. The simulation and test results on a new type of dual stator winding induction machine (DSIM) have been presented by Lipo et al. [44]. The main advantage of the drive is its improved capability to operate at low and zero speeds, maintaining high stator frequencies. It has been shown that this feature is particularly useful for implementation of speed sensorless schemes and it adds a new degree of flexibility to standard control methods currently used in ac drives. Schouten et al. [10] have studied the multiphase induction motors for integrated drives. Tests were carried out to compare the performance of a three-phase PWM drive against three-phase and six-phase square wave excited drives. It has been shown that the high torque ripple present in the three-phase square drives that leads noise and mechanical stress can be mitigated by using higher phase number motors with fully pitched windings, which are less susceptible to voltage source harmonics. Toliyat et al. [11] have presented the simulation and experimental results for a novel direct torque control (DTC) method for five phase induction machines. Test results demonstrate that DTC for five-phase induction motor can achieve a more precise flux and torque control than three-phase induction motor for the same commanded inputs. It has been shown that the combination of DTC with multi-phase induction machine can realize higher performance.

11. Conclusions

The investigations spread over the last three decades indicate the technical and economic viability of using a number of phases higher than three in induction machine. The technology of multi-phase induction machine, once developed to the stage of practical application, has many advantages to offer over conventional systems. Some of these advantages are:

- Improved reliability as the machine continues running with one of its many phases open- or short-circuited and there is not much performance degradation. This property of the multi-phase machine will be advantageous in nuclear power plants for its circulation pumps and for other similar applications in process industries, which demand high reliability.
- Reduced iron loss leading to an improved overall performance.
- Lower current per phase without increase in per phase voltage. This advantageous feature may be useful for electric vehicles and similar applications where lower, upper limit of voltage and current is desirable.
- The most advantageous feature is increase in power rating of the machine on high phase order connection in the same frame. In other words, there is a reduction in per phase power handling requirement though with enhanced modularity and fault tolerance.
Increased torque per rms ampere for the same volume machine.

Continuing advancement in the state-of-the-art of CSI converter design will inevitably lead to high power applications. With today’s devices, inverter drives in the MW range can readily achieve the use of machine with multiple three-phase groups. With non-sinusoidal voltage source, machines having more than three phases have always less rotor \( f_R \) loss and smaller torque pulsations caused by harmonics. With non-sinusoidal current sources, there is always a reduction in harmonic copper loss as compared with its three-phase counterpart. Certain space harmonics are eliminated from the air-gap flux in multi-phase machines thus reducing stray load loss and eliminating some of the cusps in the torque–speed characteristic. The coil pitch does not have to be chosen to reduce such harmonics.

Substantial progress has been made in the multi-phase induction motor drive research covering analysis, simulation, hardware development and testing. However, many problems and issues, especially those related to the development of protection schemes, efficient fault analysis tools etc, still need to be addressed to brighten the prospects for broad industrial application of this new drive technology.

References


