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Rotor flux oriented control of a symmetrical six-phase induction machine

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Abstract

Basic concepts of six-phase ac motor drives have been in existence for a number of years and were considered extensively in the eighties for safety-critical and/or high power applications. There has been an upsurge in the interest in these drives in recent times, initiated by various application areas, such as 'more-electric' aircraft, electric ship propulsion and EV/HVs. All the existing work considers an asymmetrical six-phase ac machine, with two sets of three-phase windings shifted in space by 30° (dual three-phase, split-phase, double star). In contrast to this general trend, a symmetrical six-phase induction machine, with spatial displacement between any two consecutive phases equal to 60°, is discussed in this paper. A vector control algorithm, based on indirect rotor flux orientation, is at first briefly described. Special attention is paid next to the current control issue, from the point of view of the minimum number of current controllers. An overview of the experimental test bench that utilises phase current control in the stationary reference frame is further given. Attainable performance is analysed experimentally and the results are presented for a number of operating regimes, including acceleration, deceleration, reversing and step loading/unloading transients. It is demonstrated that the achievable quality of high performance is excellent, while the standard benefits of the multiphase motor drives are retained.

Keywords: Current control; Rotor flux oriented control; Six-phase induction machine

1. Introduction

One of the first proposals of a multiphase variable speed electric drive dates back to 1969 [1]. While [1] dealt with a five-phase induction machine, six-phase (double star) induction machine supplied from a six-phase inverter was examined in [2,3]. The early interest in multiphase machines was caused by the possibility of reducing the torque ripple in inverter fed drives (operated in 180° conduction mode), when compared to the three-phase case. Another advantage of a multiphase motor drive over a three-phase motor drive is the improved reliability [4–7]. Fault tolerance is one of the main reasons behind the application of six-phase (double star) and nine-phase (triple star) induction motor drives in locomotives [4,5]. The other main reason is that for a given motor power an increase of the number of phases enables reduction of the power per phase, which translates into a reduction of the power per inverter leg. Multiphase machines are therefore often considered for and applied in high power applications.

Recent developments in the areas of 'more-electric' aircraft, electric ship propulsion and EV/HVs have led to a substantial increase in the research effort put into development of multiphase high performance drive systems. One of the most frequently considered drive structures is based on utilisation of a six-phase ac machine [8–17]. The machine type depends on the target application. By far the most frequent are the induction motor drives [9,10,12–17], primarily

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discussed in the context of high power applications. Permanent magnet synchronous motor drives [8,11] are usually considered for safety critical applications.

Detailed studies of induction machine configurations with multiple sets of three-phase stator windings and with an arbitrary number of phases have been conducted in [18] and [19], respectively. It was concluded in [18] that, in the case of a six-phase induction machine, it is advantageous to use an asymmetrical stator winding structure, with two three-phase windings spatially shifted by 30°, instead of a symmetrical winding structure with a 60° spatial shift between any two consecutive phases. The background thinking behind this conclusion is related to the pre-PWM era of VSI control, when 180° conduction mode was utilised. By using an asymmetrical six-phase machine it became possible to eliminate the sixth harmonic from the torque ripple. An asymmetrical six-phase induction motor drive has been utilised ever since, as evidenced by the surveyed references.

The main problem encountered in actual implementation of vector controlled asymmetrical six-phase induction motors is the existence of harmonic currents of the order $6n \pm 1$ ($n = 1, 3, 5, \ldots$), which do not contribute to the torque and air-gap flux production but can freely flow in the machine [14–17]. In addition to these non-torque producing currents, an asymmetrical six-phase machine with a single star point allows the flow of the triple harmonics of the order $3n$ as well. This is the reason why star points of the two three-phase windings are normally kept isolated. On the other hand, utilisation of a single star point enables enhancement of the torque production by means of the third-harmonic stator current injection [11,12]. This, however, requires connection of the star point to the mid-point of the dc-bus split-capacitor arrangement and can cause some problems due to the third harmonic current flow through the capacitors [12].

Proper control is further jeopardised by unbalanced current sharing between the two three-phase winding sets, caused by inherent asymmetries in the machine [12,13]. It is for these reasons that the standard current control in the rotating reference frame, where only stator *d*–*q* currents are regulated, does not yield a satisfactory performance of the drive. The problem can be solved by modifying the current control scheme in the rotating reference frame [20], by using four stationary current controllers in α–β and x–y sub-spaces, as discussed in [13], or by employing an advanced space vector modulation (SVM) scheme in conjunction with *d*–*q* current controllers, which ensures non-existence of voltage harmonics in the x–y sub-space [14].

In contrast to the existing solutions, this paper considers vector control of a symmetrical six-phase induction machine, with a single, isolated star point. The advantage of a single star point, when compared to the isolated double star arrangement, is an improved fault tolerance (since there are five independent currents rather than two pairs of independent currents). In order to avoid the problems associated with potential flow of harmonics of the orders $6n \pm 1$ ($n = 1, 3, 5, \ldots$) and $3n$, current control in the stationary reference frame, using machine's phase currents, is implemented.

It is demonstrated by means of experimental results that the quality of dynamic performance attainable with the proposed control scheme is excellent. Spectral analysis of the stator current shows that the unwanted low order harmonics practically do not exist or are of negligibly small values. The drive simultaneously retains the good features of multiphase motor drives, such as a reduced rating per inverter leg for given motor power and fault tolerance.

2. Configuration of the drive

Schematic illustration of the symmetrical six-phase induction motor drive is shown in Fig. 1. As already noted, spatial displacement between any two consecutive stator phases is 60° and there is a single star point. The drive is supplied from a six-phase current controlled voltage source inverter (VSI). Inverter phase current references are generated by the indirect vector controller, as explained later. Current control is exercised in the stationary reference frame, using phase currents. The reasoning behind this choice of the current control scheme will be explained in the next section, upon machine model development.

3. Modelling of the six-phase induction motor

3.1. Phase-variable model

The electrical sub-system's model of the drive in Fig. 1 is of the 12th order, since rotor cage winding is considered as a symmetrical six-phase winding as well. It can be given in matrix form with

$$\underline{v} = \underline{R}\,\underline{i} + \frac{\mathrm{d}(\underline{L}\,\underline{i})}{\mathrm{d}t}, \tag{1}$$

where

$$\underline{v} = \begin{bmatrix} \underline{v}^{\mathrm{INV}} & \underline{0} \end{bmatrix}^{\mathrm{T}} \qquad \underline{i} = \begin{bmatrix} \underline{i}^{\mathrm{INV}} & \underline{i}_{\mathrm{r}} \end{bmatrix}^{\mathrm{T}}. \tag{2}$$

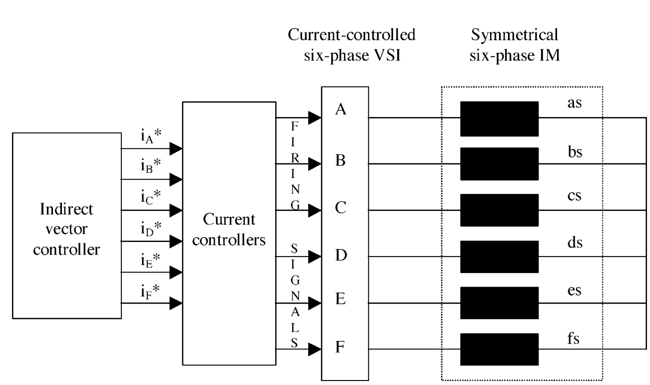

Fig. 1. Symmetrical six-phase vector controlled induction motor drive.