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A new circuit-oriented model for the analysis of six-phase induction machine performances

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ABSTRACT

This paper deals with a six-phase induction machine design for 42 V embedded applications such as electrical power steering. This machine has symmetrical 60° displacement windings which allow fault-tolerant modes. In fact, when one or more phases are opened, the machine is able to rotate with a torque reduction. A simple circuit-oriented model has been proposed in order to simulate the six-phase squirrel-cage induction machine and to predict its performances. The proposed method consists in the elaboration of an electric equivalent circuit obtained from minimal dimensional knowledge of stator and rotor parts. It takes into account only the magnetic circuit dimensions and the airgap length. A six-phase squirrel-cage induction machine of 0.09 kW, 17 V, 50 Hz, two poles has been used for the experimental set-up. A design program including the non-linear electromagnetic model has been also used with a complete description of stator and rotor cores using the iron non-linear characteristic for the final verification. The simulation results given by the two models are compared with the experimental tests in order to verify their accuracy. The harmonic analyses of stator currents are also compared to go further in the model validations.

1. Introduction

The reliability of electrical machine drives is an area of great interest for the military, aerospace and automotive industries in order to improve overall system efficiency and performances. When the operation of the drive has to be insured continuously, the parallel redundancy is often used. In this way, AC electrical machines with phase number higher than three have received considerable attention as a simple solution to provide a system redundancy. An advantage of multi-phase induction machine drives over conventional three-phase equivalent is the improved reliability by providing continuous system operation in faulted mode following the loss of excitation of one or more stator phases [1–4].

The six-phase induction machine (6PIM) with asymmetrical 30° displacement windings has been already presented [4]. It can be supplied with symmetrical currents in order to minimize space harmonics. However, the 6PIM with symmetrical 60° displacement windings is equivalent to a three-phase induction machine (3PIM) but on the contrary to 3PIM, the 6PIM can be operated with independent six phases.

The conventional *dq*0 induction machine models have been used for estimating the fundamental component of stator current, stator and rotor fluxes and the average value of the electromagnetic torque assuming a symmetrical supply and healthy machine conditions. These models facilitate the dynamic analysis when closed-loop control design is required. When the stator and the rotor are unbalanced, the classical models are hardly able to integrate the parameters characterizing the windings or squirrel-cage faults. Then, a decision on the control strategy to compensate the subsequent torque oscillation cannot be easily provided [5,6].

The aim of this paper is to show how a circuit-oriented model can be applied for predicting static and dynamic performances for a six-phase squirrel-cage induction machine with any symmetrical or asymmetrical power supply. The model allows to evaluate torque–speed, current–speed, torque–current characteristics in healthy conditions and torque and speed oscillations under stator and rotor faults. The proposed model has been obtained from the dimensions of the different slots and the stator winding distribution on a conductor-by-conductor basis. This method can be used for different types of induction machines (one-phase, three-phase, six-phase and *n*-phase induction machines). Moreover, it can be used for time-domain analysis without having to implement any

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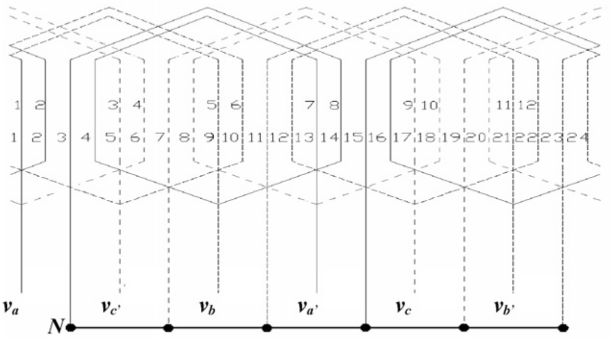

Fig. 1. 6PIM stator windings.

transformation technique [7–10]. The proposed approach gives also the way to compute the conventional 6PIM parameters for control purpose.

A 6PIM of 0.09 kW, 17 V phase voltage, 50 Hz, two poles model in healthy conditions has been given using both a design program including the induction machine non-linear model [11] and a circuit-oriented model. Then, the experimental and simulation results have been compared to validate the proposed approach. The circuit-oriented method allows the simulation of the 6PIM with the same characteristics of power supply as the one used in the test-bed. With this method, harmonic analysis of the stator current is possible in order to perform fault detection [7,12–15].

This 6PIM model is used for the design verification of electrical machines in 42 V embedded applications such as the electrical power steering (EPS). The use of a 6PIM with symmetrical with 60° displacement windings allows to have more reliability. In fact, with a failure by opening of one or more phases, the machine is still able to run with a significant electromagnetic torque only limited by the windings thermal design. In case of EPS, the drive-by-wire will be operational up to maintenance even wit this type of failure. In this way, the 6PIM drive is more fault-tolerant than any other induction machine drive with a number of phases lower than six. In detail, the 6PIM drive is equivalent to two 3PIM. Then, in the case of loss of excitation of one of these two 3PIM, it can always produce a constant but lower torque. A five-phase induction machine in the same condition of lost of three phases cannot insure the same electromagnetic torque performance and at any moment the loss of the mechanic stability can be reached.

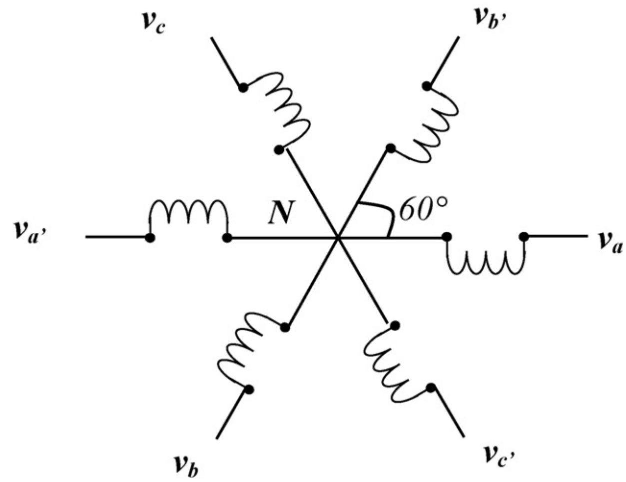

Fig. 3. Schematic diagram of the six-phase winding connections.

2. 6PIM model

2.1. Circuit-oriented model

The circuit-oriented model is obtained from the electrical parameters characterizing the individual stator coils and rotor meshes and the linked magnetic field between them assuming infinite iron permeability. Then, the parameters are computed from the stator winding connections (Fig. 1), the stator and the rotor slot specifications (Fig. 2) and the airgap length (see Appendices A and B).

The stator windings of the 6PIM are uniformly distributed with a symmetrical phase-shift of 60° in between two consecutive phases (Fig. 3). The different circuit elements associated to the stator and the rotor can be classified in term of their dependence or independence on the rotor position. The conductor resistances, self inductances of stator turns and rotor meshes, mutual inductances between stator turns and between rotor meshes, can be considered as constant. It can be seen that mutual inductances between stator turns and rotor meshes are depending on the relative position between stator and rotor [7]. For the time-domain analysis, the variation of conductor resistances due to the temperature changes is not taken into account. The constant elements can be associated with coupled branches of linear circuits (R, L) and the variable ones to control voltage sources depending on induced currents (Fig. 4) with,

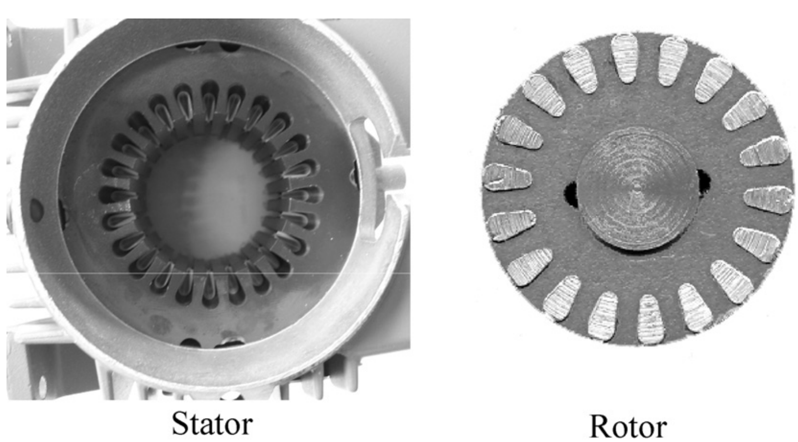

Fig. 2. Stator and rotor slots.