Available online at www.sciencedirect.com
ScienceDirect
Mathematics and Computers in Simulation 81 (2010) 194–207
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Transient model of induction machine using rotating magnetic field approach

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Received 28 July 2008; received in revised form 14 January 2010; accepted 26 February 2010
Available online 6 March 2010

Abstract

Most simulation models of electric machines use the coupled circuit approach, where the machine is considered as an electric circuit element with time-varying inductances (*abc* model) or with constant inductances (*dq0* model). On the other hand, the rotating magnetic field approach, which considers the electric machine as two groups of windings producing rotating magnetic fields and can give insight into internal phenomena of the machines, has not yet received much attention in electric machines modeling, especially for machine transient analysis. Based on the rotating magnetic field approach, this paper presents a transient model of the induction machine including main flux saturation effect. Based on the direct computation of the magnetizing fluxes of all machine windings, the model represents instantaneous main flux saturation by simply introducing a main flux saturation factor. No iteration process is involved to incorporate the saturation effects. The model combines the advantages of the *dq0* and *abc* models advantages, such as rapid computation time and nonsymmetrical conditions simulation, respectively. The simulation results and the experimental tests show advantages and verification of the model.

Keywords: Induction machine; Magnetic saturation; Transient analysis; Modeling and simulation

1. Introduction

Electric machines consist in magnetically coupled electrical circuits in the stator and the rotor. In order to establish the equations that describe the machine dynamics, inductance and current are usually used to express the flux linkage between stator and rotor and the magnetic energy stored in the air gap. The torque is found from the derivative of the magnetic field energy with respect to angular position of the rotor and can also be expressed in terms of inductance and current. Thus the electric machine can be regarded as a circuit whose inductances depend on the angular position of the rotor. This approach is called the "coupled circuit approach" and permits to study the machine's behavior by using electric circuit theory [2].

If the machine phase quantities are chosen as fundamental variables to describe the machine's behavior, the so-called *abc* model will be obtained for the three-phase electric machine. The *abc* model allows the tracking of phase currents directly without being limited by conditions of symmetry of either supply voltages or phase impedances. Thus this

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0378-4754/$36.00
doi:10.1016/j.matcom.2010.02.005

model can be used to simulate nonsymmetrical conditions, such as external and internal faults, etc. [4,9]. But the time-varying inductance makes it difficult to analyze the machine in a convenient way. Therefore, the classical theory of electrical machine analysis is usually based on the two axes model (*dq0* model), which eliminates all the time-varying inductances by using a reference frame transformation. Numerous corresponding models have been developed to analyze and simulate the machines under different conditions.

The inductance concept is defined as a linear relationship between magnetic flux and electric current. Obviously, the linear condition fails when magnetic saturation occurs. Many efforts to incorporate magnetic saturation into the *abc* and *dq0* models have been reported, as summarized in [8]. Generally, the concept of nonlinear inductance dependency on flux (or current) is introduced in these models. In order to calculate the saturated currents, an iteration solution is unavoidably used in all the saturated models to obtain the dependant saturated inductances. A well known example is the flux correction method using iteration solution introduced by K.C. Krause et al. [6] for the classical *dq0* model.

Other approaches have also been used to account for the saturation in electric machines, for example, field theory [7] and magnetic harmonic function [1]. In these approaches, the machine models are based on direct computation of flux, which eases incorporation of saturation and minimizes computation time. In [7], a mesh model based on field theory is used to simulate 3D machines but this model requires all the machine construction details. The model proposed in [1] can only simulate the machine steady state since the rotor speed is considered as constant and the torque equation is not included.

On the other hand, the rotating magnetic field approach [2], which considers the electric machine as two groups of windings (stator and rotor separately) producing rotating magnetic fields in the air gap, has received little attention, though this approach can give insight into behavior of the magnetic fields in machine. This approach analyses the machine with the aid of the magnetomotive force (MMF) and flux rather than the inductance. It is very comprehensible and usually used to explain the basic principle of rotating machines. Using this approach, the authors have succeeded in developing a transient induction machine model to incorporate saturation harmonics [10]. The model in [10] specially concentrates on modeling the squirrel-cage machine and requires the stator neutral connection to be accessible. But the saturation harmonics become important only under highly saturated condition. In most cases such as the rated operation condition, incorporating the saturation by the fundamental component is enough to represent the machine performance.

This paper sets forth complete transient modeling of three-phase induction machines using the rotating magnetic field approach and introduces a main flux saturation factor to incorporate the instantaneous saturation. The model is applicable for both the wound rotor and the squirrel-cage machines. The new model is based on the same assumptions as the classic *dq0* model and is based on direct computation of flux produced by the air gap MMF. Neither reference frame transformations nor inverse of inductance matrix are needed in the simulation procedure. Moreover, no iteration process is involved to incorporate the saturation effects. The model is verified by the experimental results.

2. Basic relationships of linear magnetic field model

From the magnetic field viewpoint, the machine can be considered as two groups of windings producing magnetic fields in the air gap, one group in the stator and the other in the rotor. The two magnetic fields rotate in the same direction. The machine torque is generated by the tendency of stator and rotor magnetic fields to line up their magnetic axes. The magnetizing flux of the machine windings are produced when the resultant air gap magnetic field acts on these windings. By making suitable assumptions, some basic expressions can be derived for the magnetizing flux and the torque in terms of field quantities.

As the classical *dq0* model, the rotating field model is based upon the following assumptions:

(1) The machine windings are symmetric and have a sinusoidal distribution.
(2) The rotor quantities are referred to the stator, i.e., the rotor has the same distributed windings as the stator.
(3) The air gap is uniform.

2.1. Air gap MMF vs. winding currents

The winding function is a good means of depicting the winding space distribution [5]. It represents in fact the MMF distribution along the air-gap per ampere current flowing in the winding. For a sinusoidal distribution machine winding