

Modelling and simulation of induction motors with inter-turn faults for diagnostics

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Abstract

This paper presents two orthogonal axis models for simulation of three-phase induction motors having asymmetrical windings and inter-turn short circuits on the stator. The first model assumes that each stator phase winding has a different number of turns. To model shorted stator turns, the second model assumes phase *as* has two windings in series, representing the unaffected portion and the shorted portion. It uses the results of the first model to transfer phase *as* to *qd* so that shorted portion is transferred to the *q* axis. Simulations results from the models are in good agreement with other studies and are compared with experiment carried out on a specially wound motor with taps to allow different number of turns to be shorted. The models have been successfully used to study the transient and steady state behaviour of the induction motor with short-circuited turns, and to test stator fault diagnostic algorithms operating in real time.

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1. Introduction

Because of costly machinery repair, extended process down time, and health and safety problems, a trend in modern industry is to focus attention and resources on fault detection and predictive maintenance strategies for industrial plant [1,2]. It is known that approximately 36% of induction motor failures are caused by failure of the stator winding, and it is believed that these faults begin as undetected turn-to-turn faults in a coil, which progress to catastrophic phase-to-phase or phase-to-ground short circuit faults [1,2]. To achieve prior warning of failure so that an orderly shut-down may be made to avoid catastrophic failure, shorted turns within a stator winding coil must be detected or predicted [1–5].

Modelling of induction motors with shorted turns is the first step in the design of turn fault detection systems [3]. Simulation of transient and steady state behaviour of motors with these models enable correct evaluation of the measured data by diagnostics techniques. The asymmetrical induction machine has been a subject of considerable interest. Brown and Butler [6] have utilized symmetrical component theory to establish a general method of analysis for operation of polyphase induction motors having asymmetrical primary connection. Jha and Murthy [7] have utilized rotating field concepts to develop a generalized theory of induction machines having asymmetrical windings on both stator and rotor. Winding-function-based models presented in Refs. [8,9], and models presented in Refs. [10,11] need motor geometrical design parameters.

The generalized theory of electrical machines incorporating orthogonal or *qd0* axis theory is generally accepted as the preferred approach to almost all types of transient and steady state phenomena [12]. The analysis of machines is greatly facilitated by the standard transformation

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to $qd0$ axis. The same transformation process can be applied to machines in which there are phase unbalances [13]. Hence, it is useful to extend this approach to also incorporate problems encountered with asymmetrical induction motors.

The aim of this paper is to present a useful and straightforward method to simulate inter-turn short circuits for diagnostic purposes. The fault can be simulated by disconnecting one or more turns making up a stator phase winding [9,14]. Firstly an induction motor model with unequal numbers of stator turns has been developed. Then using this model, a second model has been developed to simulate stator inter-turn short circuits. Models are simulated in Matlab[®] Simulink[®] and simulation results are presented. Results obtained are confirmed with a conventional asymmetrical motor model in a three-phase, non-orthogonal base, and by experimental results obtained from a specially wound motor.

2. Induction motor model with different numbers of stator turns

The model for a symmetrical three-phase induction motor is well known [15–18]. To derive equations for asymmetrical stator winding and rotor, the following assumptions have been made:

- each stator phase of the motor has a different number of turns, but uniform spatial displacement is assumed;
- magnetic saturation is not present.

With the appropriate subscripts as , bs , cs , ar , br , and cr , the voltage equations of the magnetically coupled stator and rotor circuits can be written as follows:

$$\mathbf{v}_{abc}^s = \mathbf{r}_{abc}^s \mathbf{i}_{abc}^s + p\lambda_{abc}^s, \quad 0 = \mathbf{r}_{abc}^r \mathbf{i}_{abc}^r + p\lambda_{abc}^r \quad (1)$$

where $p = d/dt$. Applying a stationary reference frame transformation to this equation yields the corresponding $qd0$ equations and Eq. (1) becomes

$$\mathbf{v}_{qd0}^s = \mathbf{r}_{qd0}^s \mathbf{i}_{qd0}^s + p\lambda_{qd0}^s, \quad 0 = \mathbf{r}_{qd0}^r \mathbf{i}_{qd0}^r - \omega_r \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \lambda_{qd0}^r + p\lambda_{qd0}^r \quad (2)$$

$$\text{where } \mathbf{r}_{qd0}^s = \begin{bmatrix} r_{11}^s & r_{12}^s & r_{13}^s \\ r_{21}^s & r_{22}^s & r_{23}^s \\ r_{31}^s & r_{32}^s & r_{33}^s \end{bmatrix} \text{ and matrix elements are given in Appendix A and assuming } r_{ar} = r_{br} = r_{cr} = r_r, \quad \mathbf{r}_{qd0}^r = r_r \mathbf{I}_{3 \times 3}.$$

In matrix notation, the flux linkages of the stator and rotor windings may be written in terms of the winding inductances and the current as

$$\begin{bmatrix} \lambda_{abc}^s \\ \lambda_{abc}^r \end{bmatrix} = \begin{bmatrix} \mathbf{L}_{abc}^{ss} & \mathbf{L}_{abc}^{sr} \\ \mathbf{L}_{abc}^{rs} & \mathbf{L}_{abc}^{rr} \end{bmatrix} \begin{bmatrix} \mathbf{i}_{abc}^s \\ \mathbf{i}_{abc}^r \end{bmatrix} \quad (3)$$

where stator and rotor inductances are

$$\mathbf{L}_{abc}^{ss} = \begin{bmatrix} L_{asas} & L_{asbs} & L_{ascs} \\ L_{bsas} & L_{bsbs} & L_{bscs} \\ L_{csas} & L_{csbs} & L_{cscs} \end{bmatrix}, \quad \text{and} \quad \mathbf{L}_{abc}^{rr} = \begin{bmatrix} L_{arar} & L_{arbr} & L_{arcr} \\ L_{brar} & L_{brbr} & L_{brcr} \\ L_{crar} & L_{crbr} & L_{crcr} \end{bmatrix}$$

Because of symmetry, stator mutual inductances have $L_{asbs} = L_{bsas}$, $L_{ascs} = L_{csas}$ and $L_{bscs} = L_{csbs}$. Similarly rotor self- and mutual inductances have $L_{arar} = L_{brbr} = L_{crcr}$, and $L_{arbr} = L_{arcr} = L_{brar} = L_{brcr} = L_{crar} = L_{crbr}$, respectively.

Those of the stator-to-rotor mutual inductances are dependent on the rotor angle (orientated with respect to stator), therefore

$$\mathbf{L}_{abc}^{sr} = \begin{bmatrix} L_{asar} \cos \theta_r & L_{asbr} \cos \left(\theta_r + \frac{2\pi}{3} \right) & L_{ascr} \cos \left(\theta_r - \frac{2\pi}{3} \right) \\ L_{bsar} \cos \left(\theta_r - \frac{2\pi}{3} \right) & L_{bsbr} \cos \theta_r & L_{bscr} \cos \left(\theta_r + \frac{2\pi}{3} \right) \\ L_{csar} \cos \left(\theta_r + \frac{2\pi}{3} \right) & L_{csbr} \cos \left(\theta_r - \frac{2\pi}{3} \right) & L_{cscr} \cos \theta_r \end{bmatrix} \quad (4)$$

and $\mathbf{L}_{abc}^{rs} = \mathbf{L}_{abc}^{sr'}$ where $(')$ means the transpose of the matrix. The coefficients L_{asar} , L_{asbr} , L_{ascr} , L_{bsar} , L_{bsbr} , L_{bscr} , L_{csar} , L_{csbr} , and L_{cscr} are peak values of stator-to-rotor mutual inductances. Because of rotor symmetry $L_{asar} = L_{asbr} = L_{ascr}$, $L_{bsar} = L_{bsbr} = L_{bscr}$, and $L_{csar} = L_{csbr} = L_{cscr}$.

The stator and rotor $qd0$ flux linkages are obtained by applying transformation to the stator and rotor abc flux linkages in Eq. (3), that is

$$\lambda_{qd0}^s = \mathbf{L}_{qd0}^{ss} \mathbf{i}_{qd0}^s + \mathbf{L}_{qd0}^{sr} \mathbf{i}_{qd0}^r, \quad \lambda_{qd0}^r = \mathbf{L}_{qd0}^{rs} \mathbf{i}_{qd0}^s + \mathbf{L}_{qd0}^{rr} \mathbf{i}_{qd0}^r \quad (5)$$

$$\text{where } \mathbf{L}_{qd0}^{ss} = \begin{bmatrix} L_{11}^{ss} & L_{12}^{ss} & L_{13}^{ss} \\ L_{21}^{ss} & L_{22}^{ss} & L_{23}^{ss} \\ L_{31}^{ss} & L_{32}^{ss} & L_{33}^{ss} \end{bmatrix}, \quad \mathbf{L}_{qd0}^{sr} = \begin{bmatrix} L_{11}^{sr} & L_{12}^{sr} & 0 \\ L_{21}^{sr} & L_{22}^{sr} & 0 \\ L_{31}^{sr} & L_{32}^{sr} & 0 \end{bmatrix}, \quad \mathbf{L}_{qd0}^{rr} = \begin{bmatrix} L_{11}^{rr} & 0 & 0 \\ 0 & L_{22}^{rr} & 0 \\ 0 & 0 & L_{33}^{rr} \end{bmatrix}, \quad \text{and}$$

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