ISA Transactions 59 (2015) 334–342

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Simulative and experimental investigation on stator winding turn and unbalanced supply voltage fault diagnosis in induction motors using Artificial Neural Networks

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ARTICLE INFO

Article history:
Received 10 March 2015
Received in revised form
23 May 2015
Accepted 3 August 2015
Available online 26 September 2015
This paper was recommended for publication by Steven Ding

Keywords:
Fault diagnosis
Induction motor
Interturn stator short circuit
Voltage unbalance

ABSTRACT

The three-phase shift between line current and phase voltage of induction motors can be used as an efficient fault indicator to detect and locate inter-turn stator short-circuit (ITSC) fault. However, unbalanced supply voltage is one of the contributing factors that inevitably affect stator currents and therefore the three-phase shift. Thus, it is necessary to propose a method that is able to identify whether the unbalance of three currents is caused by ITSC or supply voltage fault. This paper presents a feedforward multilayer-perceptron Neural Network (NN) trained by back propagation, based on monitoring negative sequence voltage and the three-phase shift. The data which are required for training and test NN are generated using simulated model of stator. The experimental results are presented to verify the superior accuracy of the proposed method.

1. Introduction

Induction motors are widely used in industry. In fact, fair self-starting capability, rugged construction, easy maintenance, low cost and reliability are contributing factors that lead induction motors to be extensively applicable [1].The condition monitoring of induction motors should be done in order to guarantee their reliability, efficiency and safety. Stator winding failures are considered as one of the most serious faults an induction motor may encounter, since they are highly probable and their damage are inextricably associated with high fault currents and high cost of maintenance [2]. Detecting stator ITSC fault is of great importance, since it probably causes a large circulating current to flow and afterward generates excessive heat in the shorted turns. Moreover, it may result in partial discharges between turns in the stator and therefore erodes the magnet wire insulation. Thus, if the diagnostic system fails to detect ITSC fault in appropriate time, it undoubtedly results in subsequent failures. Unfortunately, it is difficult to detect ITSC faults at early stages. For this reason, considerable interest has been shown in the literature to solve the difficulty in detecting this kind of fault [3–6].

Furthermore, occurrence of voltage unbalance at the motor stator terminals leads the life span of the machine to be shortened and its performance to be degraded due to increased losses, unbalanced line currents and excessive heating [7]. In [8] the most common causes of voltage unbalance are introduced as: unbalanced supply voltage, faulty operation of power factor equipment, unevenly distributed single-phase loads on the same power system, an open circuit on the primary distribution system and unidentified single phase to ground faults, to name a few.

For induction motor ITSC fault diagnosis, different kinds of fault indicators have been used in several literatures. Among various ITSC fault indicators, stator current is widely used for diagnostics purposes, for instance: current and speed [9], line currents and phase voltages [10], current and vibration signals [11], slip and symmetrical components of stator currents [12] etc. In fact, availability of the needed sensors in the existing drive system and possessing informative instinct are the main reasons that make the stator current more preferable than other fault indicators. In another seminal work, Bouzid et al. developed a Neural Network to detect ITSC fault by using phase shifts between the line currents and phase voltages [13]. Regrettably, in [13], the study is constrained by the diagnosis of ITSC fault under balanced source voltage conditions. In fact, a very important factor that is missing in [13] is that both ITSC and voltage unbalance fault lead the stator currents to lose its balance and therefore alter the phase shift between the current and voltage of each phases similarly. Thus,

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http://dx.doi.org/10.1016/j.isatra.2015.08.001
0019-0578/© 2015 Published by Elsevier Ltd. on behalf of ISA.

another fault indicator should be utilized alongside stator current, in order to distinct between ITSC and unbalanced supply voltage fault. Extensive research efforts have been put forth to detect unbalanced supply voltage on electric motors using negative sequence current [14–18]. Although negative sequence current has attractive features to reveal unbalanced supply voltage and stator faults, it is highly sensitive to inherent machine asymmetry. Hence, this paper considers fault indicators which are able to diagnose ITSC fault and to distinguish it from the supply voltage unbalance while they are immune from inherent machine asymmetry. Further, unlike previous model-based methods [19] in which the model of stator was always needed during the fault diagnosis procedure, this research proposes a less model dependent methodology that uses the stator model only to collect data for training and testing the Neural Network under various faulty conditions and afterwards the model would not be required anymore.

The present paper is organized as follows. The model of induction motor including ITSC fault that is used to get simulated database for training and test procedure of NN is described in Section 2. In Section 3, the behavior of selected fault indicators is investigated. The description of the proposed diagnostic system for identifying ITSC fault and unbalanced voltage based on NN are detailed in Section 4. In Section 5, efficiency of the proposed method is demonstrated by the use of experimental data's coming from 3 kW squirrel-cage induction motor. Finally, the conclusion is provided in Section 6.

2. Modeling of three-phase induction motor

Studying the behavior of induction motors under different fault conditions by creating real faults into the motor and monitoring its evolution does not seems sensible since firstly created faults can be dangerous for the motor and might lead to the destruction of the motor [20]; And secondly, presence of other uncertainties in real systems, like inherent machine asymmetry, non-ideal sensors, noise and disturbances, may cause the achieved results not to be reliable. Thus, an accurate model of faulty induction motor can be useful in this regard.

2.1. Healthy model

In order to model the stator of a healthy induction motor, it is better to use the basic equations of induction motor in *dq* stationary reference frame. Dynamic equations of a three-phase healthy induction motor stand as follows [21]:

Stator (subscript with s) voltage equations

$$v_{as} = R_s i_{as} + \frac{d\lambda_{as}}{dt} \tag{1}$$

$$v_{bs} = R_s i_{bs} + \frac{d\lambda_{bs}}{dt} \tag{2}$$

$$v_{cs} = R_s i_{cs} + \frac{d\lambda_{cs}}{dt} \tag{3}$$

where winding flux, λ, given by

$$\frac{d\lambda_{qs}}{dt} = v_{qs} - r_s i_{qs} - \omega\lambda_{ds} \tag{4}$$

$$\frac{d\lambda_{ds}}{dt} = v_{ds} - r_s i_{ds} + \omega\lambda_{qs} \tag{5}$$

2.2. Model under ITSC fault

The schematic of an induction motor with ITSC fault on a single phase is shown in Fig. 1. An accurate analytical model to describe ITSC fault has been presented in [22].

Assuming that motor operates under an ITSC fault in phase A, the equations of faulty model can be expressed as:

Equations of stator winding flux in *dq* frame

$$\frac{d\lambda_{qs}}{dt} = v_{qs} - r_s i_{qs} + \omega\lambda_{ds} + \frac{2}{3}\mu r_s i_f \cos\theta \tag{6}$$

$$\frac{d\lambda_{ds}}{dt} = v_{ds} - r_s i_{ds} + \omega\lambda_{qs} + \frac{2}{3}\mu r_s i_f \sin\theta \tag{7}$$

Equations of short circuit winding flux

$$\frac{d\lambda_{as2}}{dt} = r_f i_f - \mu r_s (i_{ds}\cos\theta + i_{qs}\sin\theta - i_f) \tag{8}$$

The stator and winding currents in *dq* frame

$$i_{qs} = \lambda_{qs} a_1 - \lambda_{qr} a_2 + (L_r a_3 - L_m a_4) i_f \cos\theta \tag{9}$$

$$i_{ds} = \lambda_{ds} a_1 - \lambda_{qr} a_2 + (L_r a_3 - L_m a_4) i_f \sin\theta \tag{10}$$

$$i_f = (-\lambda_{as2} + (a_5 i_{qs} + a_6 i_{qr})\cos\theta + (a_5 i_{qs} + a_6 i_{qr})\sin\theta)/a_4 \tag{11}$$

Note that the constant coefficients a_i are shown in Table 1. Also i, v, r, L_l and L_m are representing currents, voltages, resistance, leakage and mutual inductance respectively.

Having simulated the model discussed above by MATLAB, the stator current of the induction motor under various ITSC fault is obtained. The simulated motor is 3 kW induction motor having 250 turns per phase winding on the stator. The characteristics of the motor used to obtain the simulated results are shown in Table 2. Fig. 2 shows the simulated three-line's currents (a) in healthy condition, (b) under a stator fault of 50-shorted turns on one of the three phases and (c) under unbalanced supply voltage that affects only one phase voltage magnitude with 5% of the rated phase voltage. This figure clearly shows that both ITSC and voltage unbalance fault lead the stator currents to lose their balance and therefore change the three-phase shifts.

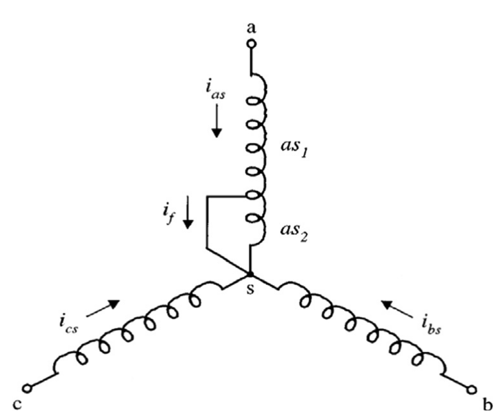

Fig. 1. Schematic of three-phase winding with ITSC fault on phase A.

Table 1
Constant coefficients of currents' equations.

a_0	a_1	a_2	a_3	a_4	a_5	a_6
$L_s L_r - L_m^2$	$\frac{1}{a_0 L_s}$	$\frac{L_m a_1}{L_r}$	$\frac{2}{3}\frac{\mu L_s}{a_0}$	$\frac{2}{3}\frac{\mu L_m}{a_0}$	μL_s	μL_m