Electrical faults and their effects on induction machines

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Abstract
Induction machines are commonly used as "backbones" in industrial applications and power systems. Although these devices have high reliability, they are usually subject to abnormal operating conditions that may lead to parameter changes. In this paper, effects of some electrical faults, open-circuit and short-circuit faults, on induction machine parameters are discussed in detail. It has been shown that, the envelope produced in stator currents has a different profile and frequency depending on the fault location. These effects can be used when monitoring the condition of the machine to reduce the time required to diagnose the malfunction. MATLAB SIMULINK is used to analyse and simulate the induction machine under both healthy and faulty conditions.

Keywords
Induction machines, condition monitoring, fault diagnosis.

1. Introduction

Induction machines (IM) have been intensively utilized and they are considered as critical components in a large variety of many industrial processes and applications including Model Predictive Control (MPC) [1], sensorless control [2], , and condition monitoring [3]. Although these devices have high reliability[4], they are usually subjected to abnormal operating conditions that might lead to unavoidable parameter changes and different modes of failures/faults. Due to the high cost of operation and maintenance, many efforts and researches have been conducted in order to reduce their cost and improve their efficiency, availability and reliability.

One approach of IM condition monitoring is to use external measurements of voltage, current, speed, and torque with optimization algorithms to check characteristic parameters of the machine and detect the fault accordingly. Using such approach, many cases can be encountered where the outputs of a model fit to some measurements, even if the parameters are erroneous. Consequently, experimental results are not sufficient for validating the estimation technique. The obtained result is not univocally determined and it depends on the used model and the initialization of the algorithm [5-7]. To uniquely identify all parameters, it is advisable to follow one of two procedures: either changing the models with a reduced number of parameters or introducing additional and independent algebraic equality or inequality constrains which is known as a prior, good initialization is

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considered as a restriction. The restrictions can be made by adding further information concerning the constructive details of the machine. In this line, reducing the search space dimension of optimization algorithms provides good results and might leads to a unique solution. In this paper, effects of some electrical faults on the IM electrical parameters, resistances and inductances, and how can deal with them during fault monitoring is introduced. Consequently, some assumptions can be made that can be regarded as an appropriate.

To study the effect of malfunctions on IM parameters, it is necessary to identify those parameters and factors affecting their value. In general, the circuit of the IM consists of resistors and inductors, which in turn are divided into several types.

A. *The self-inductance*

The self-inductance in stator and rotor windings consists of magnetizing and leakage inductance. For healthy machine, the windings are identical and therefore the self-inductance of all stator windings will be identical.

$$L_A = L_B = L_C = L_{ms} + L_{\sigma s} \quad (1)$$

The magnetizing inductance can be expressed as:

$$L_{ms} = \frac{\mu_o lrN_s^2\pi}{4g} \quad (2)$$

The self-inductance of the rotor is similar to that of the stator windings:

$$L_a = L_b = L_c = L_{mr} + L_{\sigma r} \quad (3)$$

where:

$$L_{mr} = \frac{\mu_o lrN_r^2\pi}{4g} \quad (4)$$

where N_s and N_r are the effective number of turns of the stator and rotor windings, r is the radius of the motor cross section, l is the length of the motor, and g is the air gap radial length.

B. *The mutual inductance*

Mutual inductances exist between all windings of both stator and the rotor. There are four different types of mutual inductance: stator-to-stator (mutual inductance between two different stator windings), rotor-to-rotor (mutual inductance between two different rotor windings), stator-to-rotor (mutual inductance between a stator and rotor winding), and rotor-to-stator (mutual inductance between a rotor and stator winding). Stator-to-stator mutual inductance can be expressed by:

$$L_{xsys} = \frac{\mu_o lrN_s^2\pi}{4g} Cos\,\theta_{xsys} \quad (5)$$

where L_{xsys} is the inductance between any stator winding x and any other stator winding y, and θ_{xsys} is the angle between the stator winding x and y.

Using equation (2), equation (5) can be modified:

$$L_{xsys} = L_{ms} Cos\,\theta_{xsys} \tag{6}$$

For healthy machines and when considering the winding distribution, it can be found that only possible displacement between two stator windings are 120° and 240° in both directions. This implies $Cos\theta_{xsys}$ in equation (6) can be evaluated as:

$$Cos\,\theta_{xsys} = Cos(\pm 120^o) = Cos(\pm 240^o) = -0.5 \tag{7}$$

From equations (5-7); the expression describing the mutual inductances between any two stator windings can be simplified as:

$$L_{AB} = L_{AC} = L_{BA} = L_{CA} = L_{CB} = -0.5\,L_{ms} \tag{8}$$

Similar, the rotor-to-rotor mutual inductances can be given by:

$$L_{ab} = L_{ac} = L_{ba} = L_{CA} = L_{cb} = -0.5\,L_{mr} \tag{9}$$

The stator-to-rotor mutual inductances are functions of the rotor position according to the following relationship:

$$L_{xsyr} = L_{sr} Cos\,\theta_{xsyr} \tag{10}$$

where L_{xsyr} is the inductance between any stator winding x and any other rotor winding y, and θ_{xsyr} is the angle between them. The expression L_{sr} in equation (10) is given by:

$$L_{sr} = \left(\frac{N_s}{2}\right)\left(\frac{N_r}{2}\right)\frac{\mu_o l r \pi}{g} \tag{11}$$

C. ***The resistance.***

The value of resistance is given by:

$$R = \frac{\rho l}{A} \tag{12}$$

where R is the resistance (Ω), ρ is the resistivity (Ω.m), l is the cable length (m), and A is the cross-sectional area (m^2) of the cable.

Based on previous equations; inductances of IMs are calculated based on the geometrical characteristics of the machine (the number of turns, the number of poles, the radius of the motor, the effective length of the motor, and the air gap radial length) [8, 9]. For open-circuit fault, it is acceptable to assume that the inductance changes are negligible due to its insignificant influence compared to the resistance changes [10-12]. In contrast, when a short-circuit fault occurs in a given phase, the corresponding number of winding turns will decrease and here both changes of resistances and inductances of the shorted windings have to be taken into account [9, 10, 13]. For faulty machine, the inductances will not exceed the healthy values and, as a result, it is possible to use the healthy set as an upper limit for the search space which significantly increases the accuracy and reduces the computation time and allow for logical constrains.

2. faults effects on the induction Machines

In this section, effects of some electrical faults, open-circuit and short-circuit faults, on IM parameters are discussed in details.

A. *Stator short circuit fault.*

In both faulty and healthy motor with sinusoidal distribution of windings, the self-inductance of each winding is proportional to the square of the counts of turns, and the mutual inductance of two windings is proportional to the product of the counts of turns in the two windings. When a short circuit between any (stator/rotor) turns arises in a given phase, the corresponding number of winding will decrease [14]. In this situation, both changes of stator/rotor resistances and inductances due to the short circuit have to be taken into account.

For stator fault, the same for the rotor, the leakage inductance of short turns is $\mu L_{\sigma s}$, where μ is the magnitude of the fault in terms of the percentage of the faulted phase (the fraction of shorted turns). In addition, the matrix of the inductance and resistance of the rotor, which is healthy in here, in faulty and faultless motor are identical and will not be affected [15, 16]. A much better approximation of the reality to consider the leakage inductance of each sub windings as being proportional to its squared turns number. As a result, an approximate relationship between the portion of short circuit and the change of winding inductance in stator is to consider the leakage inductance to be proportional to squared turns number [17]. It is clear that, the stator electrical parameters R_s, L_{ss}, L_{sr}, and L_{rs} are directly affected.

Let μ_{SA}, μ_{sB}, and μ_{sC} be the percentage of the remaining un-shorted stator windings in stator phases *A*, *B*, and *C* respectively. The modified stator resistance matrix R_s in ABCabc reference frame is given by:

$$R_s^* = \begin{bmatrix} R_s + \Delta R_A & 0 & 0 \\ 0 & R_s + \Delta R_B & 0 \\ 0 & 0 & R_s + \Delta R_C \end{bmatrix} \qquad (13)$$

where ΔR_A, ΔR_B, and ΔR_C represent stator resistance changes in phase *A*, *B*, and *C* respectively. The modified stator inductance matrix L_{ss} in *ABCabc* model is given by:

$$L_{ss}^* = \begin{bmatrix} \mu_{sA}^2 L_s & \mu_{sA}\mu_{sB}L_{ms} & \mu_{sA}\mu_{sC}L_{ms} \\ \mu_{sB}\mu_{sA}L_{ms} & \mu_{sB}^2 L_s & \mu_{sB}\mu_{sC}L_{ms} \\ \mu_{sC}\mu_{sA}L_{ms} & \mu_{sC}\mu_{sB}L_{ms} & \mu_{sC}^2 L_s \end{bmatrix} \qquad (14)$$

The modified stator-to-rotor mutual inductance matrix L_{sr} is given by:

$$L_{sr}^{*} = \begin{bmatrix} \mu_{sA}\cos(\theta_r) & \mu_{sA}\cos(\theta_r + \frac{2\pi}{3}) & \mu_{sA}\cos(\theta_r - \frac{2\pi}{3}) \\ \mu_{sB}\cos(\theta_r - \frac{2\pi}{3}) & \mu_{sB}\cos(\theta_r) & \mu_{sB}\cos(\theta_r + \frac{2\pi}{3}) \\ \mu_{sC}\cos(\theta_r + \frac{2\pi}{3}) & \mu_{sC}\cos(\theta_r - \frac{2\pi}{3}) & \mu_{sC}\cos(\theta_r) \end{bmatrix} \quad (15)$$

The modified rotor-to-stator mutual inductance matrix L_{rs} can be obtained as:

$$L_{rs}^{*} = \left[L_{sr}^{*}\right]^{T} \quad (16)$$

In these matrices, L_s is the inductance of the stator, L_{ms} is the mutual inductance between the stator windings, L_{sr} is the peak value of the stator-to-rotor mutual inductance, and the superscript T denotes the transpose of the matrix. While the rotor inductance L_{rr} remaining unchangeable for faulty stator.

B. *Rorot open circuit fault.*

For squirrel cage IM, broken rotor bars cause asymmetry of resistances and inductances in the rotor phases. This impact of broken bars fault can be modelled by unbalancing the stator resistances while the inductance changes are negligible due to its insignificant influence compared to the resistance changes [12, 18, 19]. Broken bars are similar to open circuit faults in wound rotor induction machines. As a result, for open circuit faults it is acceptable to assume all inductances to be constant and allow the resistances to change.

3. Simulation Study

In order to investigate the effects of electrical faults on the IM, the machine was implemented in Matlab/Simulink. A three-phase, 1.5 kw. 50 Hz, 415 v, 2-poles wound rotor induction motor was used in this paper to obtain stator current waveforms for both healthy and faulted operating conditions. The nominal parameters values of the motor are: R_s = 4.417 Ω, R_r = 7.686 Ω, L_s = 0.267 H, L_r = 0.267 H, and l_m = 0.255 H. Stator currants and output torque waveforms were analysed for different cases including healthy and faulty IM. Winding asymmetry fault is simply implemented by changing the stator/rotor resistances to different values that differ from healthy one, which is recognized as an acceptable approach [20, 21]. Fig. 1 shows a block diagram of the Simulink model used in the this paper.

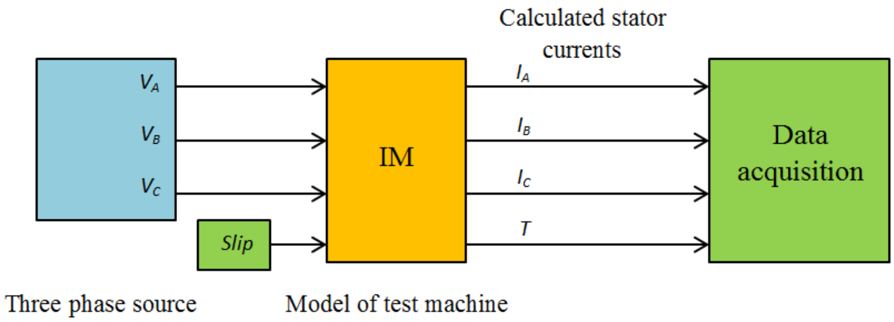

Fig. 1. Simulink model showing machine mathematical model combined with practical data for identifiability analysis.

A. *The three phase stator current profile:*

Rotor faults produce in the three phase IM a phenomena known as an 'envelope'. The envelope is a geometric 'line shape' of a modulation in the amplitude of the three-phase stator current due to the faults of the rotor of induction motor. This envelope is cyclically repeated at a rate equal to twice the slip frequency given by *2sf*, where *f* is power supply frequency, Fig. 2.

Healthy rotor has a rotating magnetic field nature with a perfect periodic profile over two pole pitches; where a pole pitch is defined as the peripheral distance between identical points on two adjacent poles, leading to a circular trace of the magnetic field's space vector. But, once a rotor develops any fault, the periodical profile is no longer observed over the two pole pitches of the rotor containing the fault due to the fact that for open circuit fault no induced current can flow in the opened winding and for short circuited fault the induced voltage in the shorted winding will be zero. As a result, the magnetic field neutral plan orientation differs from the position for the healthy, leads to angular shifting in the rotor magneto-motive force *mmf* waveform. This angular shifting is a function of the kind of the fault and the geometry distribution of the faulty winding around the rotor, Fig. 3. This angular shifting varies with time in a cyclical manner [22, 23]. The distortion of the rotor's magnetic field orientation and the resulting local saturation in the rotor lamination around the region of the faulted winding are leading to quasi-elliptical trace of the magnetic field's space vector. As a result, these effects modulate in sequential manner the three phase stator currents. This modulation of the three phase stator current is known as an envelope. On the other hand, stator winding faults cause a profile modification of the three phase stator currents and leading to a cyclically repeated envelope at a rate equal to the power source frequency *f*. The fault mainly affects the stator current of the faulty phase in both profile and peak value, while the stator currents of the other healthy phases are less affected. As a result, the stator current profile of each phase is not equally affected by the fault and the three phase stator profile modulation is referred to as an envelope. In stator faults, the frequency of repetition of this envelope is not a function of the slip frequency, it is just a function of the power source frequency *f*.

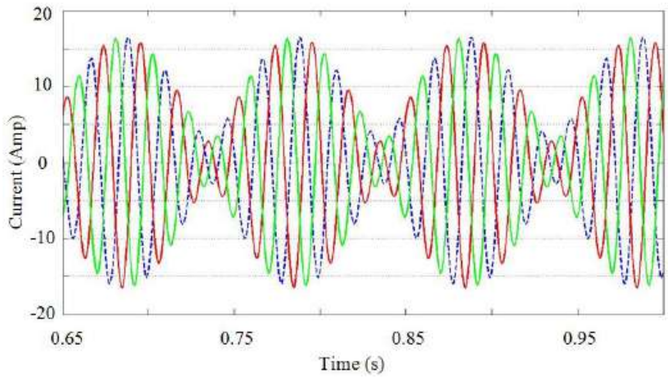

Fig. 2. Three Phase stator current envelope for rotor faults.

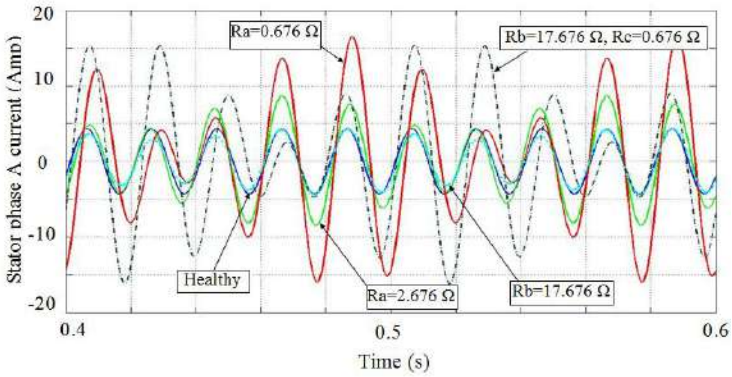

Fig. 3. Stator current envelope for different rotor faults.

B. *The output torque profile:*

The torque of the IM is dependent of the three phase stator current. The torque of an IM with faulty rotor is modulated proportionally to the three phase stator current. The three phase current envelope of faulty rotor IM produces an oscillation in the torque profile repeated at the same frequency rate, *2sf* ,of the envelope of the stator current. Consequently, The period of the oscillation for torque is given by:

$$T_{torque} = \frac{1}{2sf} \qquad (17)$$

The amplitude and the frequency of the torque are proportional to the motor load. If the motor is loaded, the amplitude of the torque increases and as a result the profile modulation of the envelope of the torque is more obvious. For no loaded motor the amplitude and the oscillation of the torque are very low. The output torque is a function of the kind of the fault and the geometry distribution of the faulty winding around the rotor. Fig. 4 shows output torque for the healthy, different faulty machines, and the period of torque oscillation.

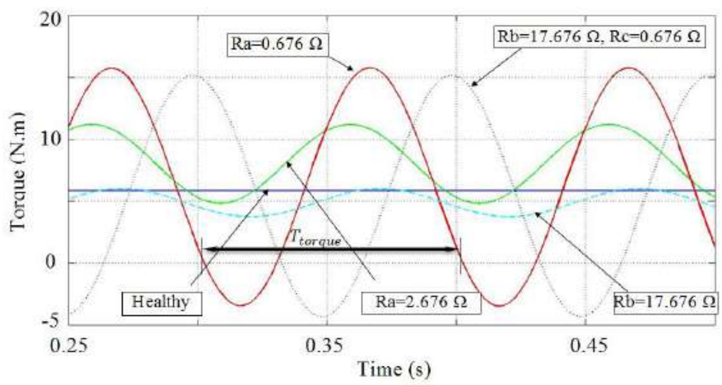

Fig. 4. Output torque envelope for different rotor faults.

C. *Stator faults vs. rotor faults indicated from stator current:*

As mentioned before, rotor faults produce an envelope in the three phase stator current repeated at a rate equal to *2sf*, where *f* is the power source frequency. On the other hand, stator faults cause a profile modification of the three phase stator currents and leading to a cyclically repeated envelope at a rate equal to the power source frequency *f*. For mixed faults, each phase has stator current that has an envelope with different amplitude and same frequency *2sf*. See Fig. 5, Fig. 6, Fig. 7, and Fig. 8.

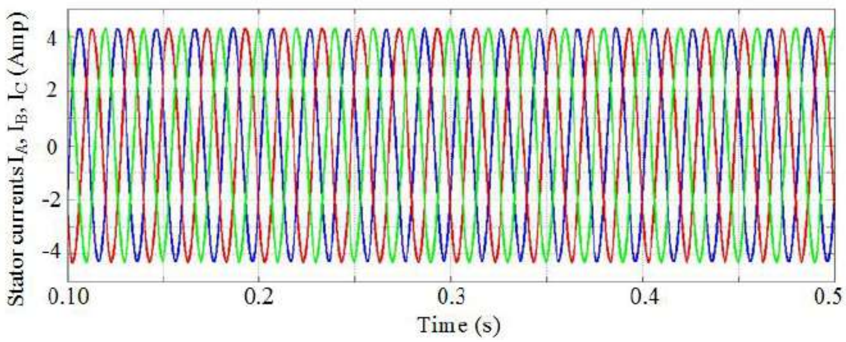

Fig. 5. Healthy stator current waveform.

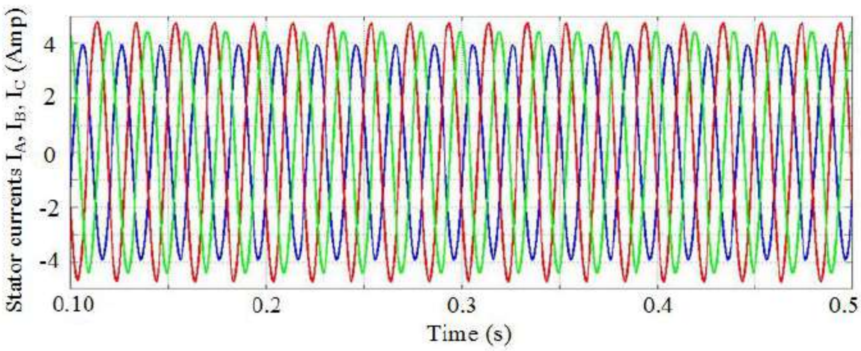

Fig. 6. Stator faults-stator current waveform.

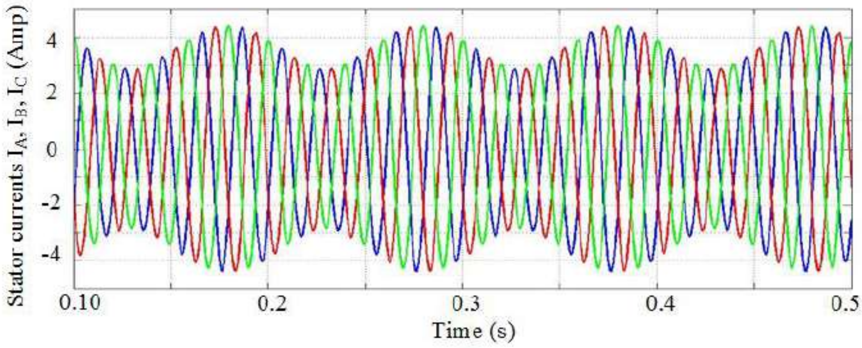

Fig. 7. stator current waveforms for rotor faults.

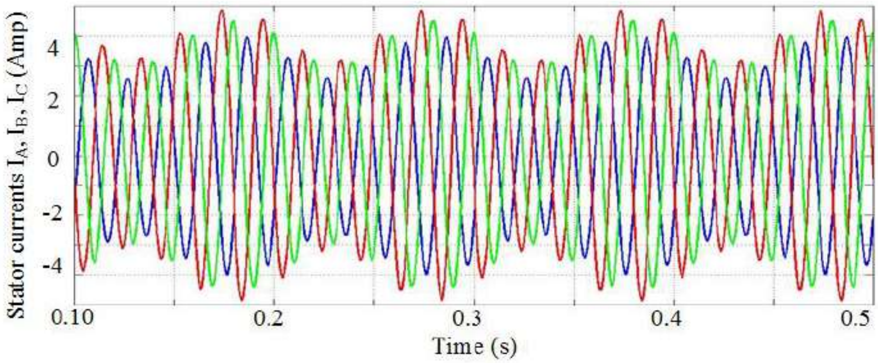

Fig. 8. stator current envelope for Mixed faults.

4. Conclusion

It has been shown that, the envelope produced in stator currents has a different profile and frequency depending on the fault location. Rotor faults produce an envelope in the three phase stator current repeated at a rate equal to *2sf*, where *f* is the power source frequency. On the other hand, stator faults cause a profile modification of the three phase stator currents and leading to a cyclically repeated envelope at a rate equal to the power source frequency *f*. For mixed faults, each phase has stator current that has an envelope with different amplitude and same frequency *2sf*. As a result, this can be used as an initialization algorithm for condition monitoring approaches in order to increase the accuracy and reduce the computation time. It appears that, it is acceptable to model the impact of open circuit fault by unbalancing the resistances while inductances' changes are neglected and as a result they can be assumed equal to the healthy one. In contrast, both resistances and inductances should be taken into account when considering IM short circuit faults.

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