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Open-circuit fault diagnosis in three-phase induction motor using model-based technique

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Abstract: The presence of an open-circuit fault subjects a three-phase induction motor to severely unbalanced voltages that may damage the stator windings consecutively causing total shutdown of systems. Unplanned downtime is very costly. Therefore, fault diagnosis is essential for making a predictive plan for maintenance and saving the required time and cost. This paper presents a model-based diagnosis technique for diagnosing an open-circuit fault in any phase of a three-phase induction motor. The proposed strategy requires only current signals from the faulty machine to compare them with the healthy currents from an induction motor model. Then the errors of comparison are used as an objective function for a genetic algorithm that estimates the parameters of a healthy model, which they employed to identify and localize the fault. The simulation results illustrate the behaviours of basic parameters (stator and rotor resistances, self-inductances, and mutual inductance) and the number of stator winding turn parameters with respect to the location of an open-circuit fault. The results confirm that the number of stator winding turns are the useful parameters and can be utilized as an identifier for an open-circuit fault. The originality of this work is in extracting fault diagnosis features from the variations of the number of stator winding turns.

Key words: induction motor, model-based diagnosis, number of turns, open-circuit fault

1. Introduction

Failure threatens all electrical machines, even those that are built in robust and rugged construction such as induction motors [1, 2]. Early diagnosis of a fault is helpful in minimizing the unwanted shutdown and reducing the cost of unplanned maintenance [3]. Hence, using

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predictive maintenance is useful in overcoming the downtime costs and increases the efficiency of systems [4, 5]. The category of induction motor faults includes two main sets: mechanical and electrical faults. The mechanical faults are bearing and broken rotor faults. The electrical faults' set contains an open circuit and short circuit of stator windings [6].

The open-circuit fault in a three-phase induction motor is referred to as single phasing, which means that one of the three-phases lost its connection with the supply. During the presence of an open-circuit fault, the machine will be subjected to severely unbalanced voltages and overheating due to the flow of high currents in the remaining healthy phases [7]. Therefore, the stator windings can be damaged by excessive generated heat.

Some of the studies on open-circuit fault diagnosis in a three-phase induction motor are presented in [8–10]. The diagnosis strategy in [8] used optimization methods to estimate the stator and rotor resistances of a three-phase wound rotor type induction motor. In this strategy, the announcement of the faulty phase, whether in the stator or rotor, is based on the magnitude of resistance where the faulty phase has the largest resistance value. Other intelligent techniques such as the fuzzy logic system [9] and support vector machine [10] are utilized after learning by practical data for recognizing the healthy state from the faulty state due to an open-circuit fault.

The first objective of this paper is to develop the healthy model of a three-phase induction motor, which is presented in [11] in order to consider the state of one phase as an open-circuit. The second objective is studying the behaviours of induction motor parameters with respect to the occurrence of that fault and extracting useful features to detect and localize the presence of an open-circuit fault.

2. Model-based diagnosis method

The model-based method is initially used in the early 70s, the basic idea of model-based technique, which is also known as analytical redundancy, is to generate residual(s) from the comparison between the output of a system and its equivalent software model. Hence, if the residual value is greater than a predefined threshold value (ideally equal to zero), then the system is suffering from an abnormal condition. Otherwise, the system is in a healthy state condition [12].

For this work, the model-based technique is employed for the diagnosis of an open-circuit fault in three-phase induction motors. Fig. 1 demonstrates the framework of the suggested diagnosis method. In that figure, the three-phase currents of the faulty induction motor are compared with the currents of a healthy mathematical model (software model). The output of comparison, which is known as residual, is handled by the performance index sum square of errors and that can be expressed as in the following equation, (1):

$$F(\boldsymbol{X}) = \left(ia - ia^{\wedge}\right)^2 + \left(ib - ib^{\wedge}\right)^2 + \left(ic - ic^{\wedge}\right)^2, \tag{1}$$

where: ia, ib and ic represent the real instantaneous three-phase current of an induction motor and $ia^{\wedge}$, $ib^{\wedge}$ as well as $ic^{\wedge}$ represent the corresponding three-phase current that is generated by the healthy mathematical model.

In order to track the behaviours of induction motor parameters, the above equation, (1), is used as the objective function of an optimization method (a genetic algorithm in this work) to estimate the corresponding deviation in the faulty machine parameters. The vector $\boldsymbol{X}$ of the objective function $F(\boldsymbol{X})$ represents those parameters.

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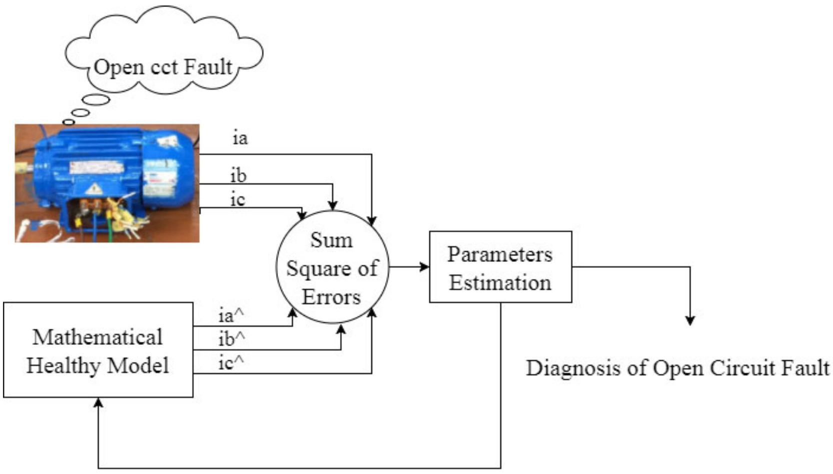

Fig. 1. Framework for open-circuit fault diagnosis in three-phase induction motor

3. Mathematical model of three-phase induction motor and genetic algorithm

3.1. Healthy mathematical model

The mathematical model of a three-phase induction motor, which is used in this paper, is adopted from [11]. The model is in the *q-d* reference frame as it is simpler and requires less computation time in comparison with an *abc* reference frame model. This model has an assumption of asymmetrical stator windings, i.e. the number of turns in each phase is different. Hence, the number of turns in phase "*a*", phase "*b*", and phase "*c*" is represented by *Nas*, *Nbs*, and *Ncs*, respectively.

The basic equations of the model are given in the following equations, where the stator and rotor voltages are with superscripts *s* and *r*, respectively:

$$V^s_{abc} = r^s_{abc}\, i^s_{abc} + \frac{\mathrm{d}}{\mathrm{d}t}\lambda^s_{abc}\,, \tag{2}$$

$$0 = r^r_{abc}\, i^r_{abc} + \frac{\mathrm{d}}{\mathrm{d}t}\lambda^r_{abc}\,. \tag{3}$$

After transformation of the above equations to the stationary *q-d* reference frame, new *q-d* equations can be written as:

$$V^s_q = \frac{2}{3}\left[V_{ag} - \frac{1}{2}\left(V_{bg} + V_{cg}\right)\right], \tag{4}$$

$$V^s_d = \frac{1}{\sqrt{3}}\left(-V_{bg} + V_{cg}\right), \tag{5}$$

where V_{ag}, V_{bg} and V_{cg} are the three phase supply voltages.

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The flux linkage equations in the q-d stationary reference frame are written in matrix form as below (6)

$$\begin{bmatrix} \lambda q^s \\ \lambda d^s \\ \lambda q^r \\ \lambda d^r \end{bmatrix} = \begin{bmatrix} \int (Vq^s - r11^s iq^s - r12^s id^s)\,\mathrm{d}t \\ \int (Vd^s - r21^s iq^s - r22^s id^s)\,\mathrm{d}t \\ \int (wrd^r - rr\,iq^r)\,\mathrm{d}t \\ -\int (wrq^r + rr\,id^r)\,\mathrm{d}t \end{bmatrix}, \tag{6}$$

$$\begin{bmatrix} r11^s & r12^s & r13^s \\ r21^s & r22^s & r23^s \\ r31^s & r32^s & r33^s \end{bmatrix} =$$

$$= \begin{bmatrix} \frac{2}{3}\left(\frac{Nas}{Ns}rs+\frac{1}{4}\frac{Nbs}{Ns}rs+\frac{1}{4}\frac{Ncs}{Ns}rs\right) & \frac{\sqrt{3}}{6}\left(\frac{Nbs}{Ns}rs-\frac{Ncs}{Ns}rs\right) & \frac{1}{3}\left(2\frac{Nas}{Ns}rs-\frac{Nbs}{Ns}rs-\frac{Ncs}{Ns}rs\right) \\ \frac{\sqrt{3}}{6}\left(\frac{Nbs}{Ns}rs-\frac{Ncs}{Ns}rs\right) & \frac{1}{2}\left(\frac{Nbs}{Ns}rs+\frac{Ncs}{Ns}rs\right) & \frac{-\sqrt{3}}{12}\left(\frac{Nbs}{Ns}rs-\frac{Ncs}{Ns}rs\right) \\ \frac{1}{6}\left(2\frac{Nas}{Ns}rs-\frac{Nbs}{Ns}rs-\frac{Ncs}{Ns}rs\right) & \frac{-\sqrt{3}}{6}\left(\frac{Nbs}{Ns}rs-\frac{Ncs}{Ns}rs\right) & \frac{1}{3}\left(\frac{Nas}{Ns}rs+\frac{Nbs}{Ns}rs+\frac{Ncs}{Ns}rs\right) \end{bmatrix}, \tag{7}$$

where Ns is the reference number of turns.

The rotor speed equation is expressed as:

$$wr(t) = \frac{P}{2J}\int (Tem + Tmech - Tdamp)\,\mathrm{d}t, \tag{8}$$

where: P is the number of poles, J is the moment of inertia. $Tdamp$, $Tmech$, and Tem are the damping torque, the mechanical torque, and the electromechanical torque, respectively. The latest one can be calculated from the following equation:

$$Tem = \frac{3}{2}\frac{P}{2}\left(\lambda d^s iq^s - \lambda q^s id^s\right). \tag{9}$$

The equations of a three-phase induction motor in the q-d reference frame have been implemented using the Matlab/Simulink environment.

3.2. Simulation of the open-circuit fault

Based on the equations of the healthy motor model, a new faulty motor model has been developed to simulate the actual motor operating with an open-circuit fault on phase "a". This is obtained through multiplying the number of stator winding turns of the faulty phase (Nas) by a large number at the instance of fault occurrence specified by the step function, as shown in Fig. 2. This action emulates a high-value series resistance to be inserted between the voltage source and the faulty phase in order to make the current almost zero. As suggested in a model-based diagnosis approach, the current signals of the developed faulty model are compared with corresponding current signals of the healthy model.

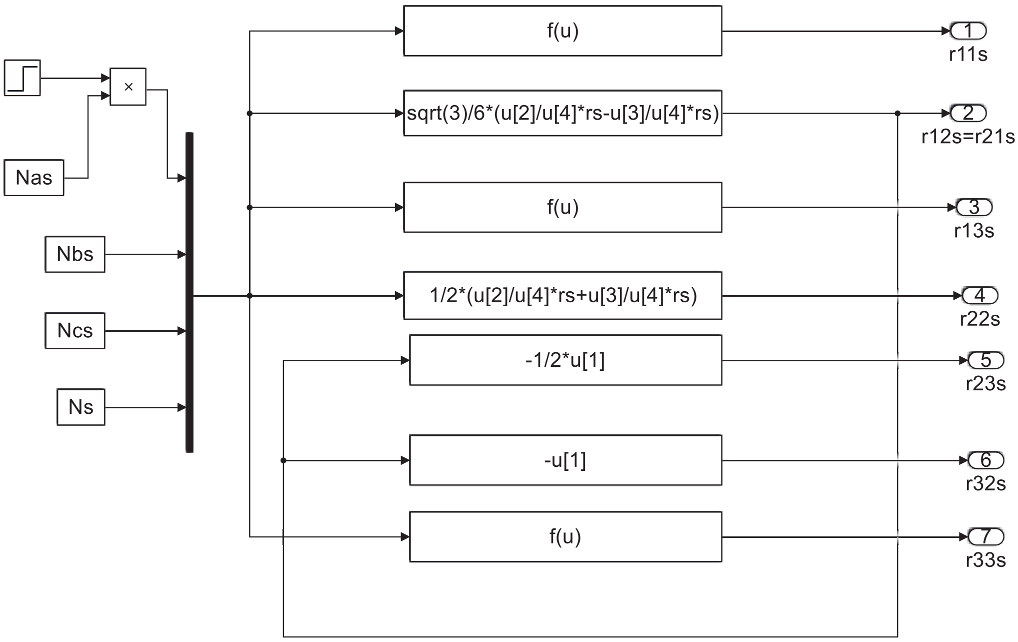

Fig. 2. Modified stator resistances equations for open-circuit fault implementation

3.3. Genetic algorithm

A genetic algorithm (GA) is one of the optimization methods that is inspired by nature. The algorithm tries to find the global solution from an initial population by using two kinds of operation, crossover and mutation. At each generation, a genetic algorithm replaces the worst parent (chromosome) with a better child until the convergence of solution is obtained [13–16]. The mission of the genetic algorithm in this work is to minimize the objective function, which is given in (1), where the real currents' data under open-circuit fault are gathered from the modified model for comparison with the simulated healthy currents. The parameters of a genetic algorithm chromosome are: stator and rotor resistances, stator and rotor leakage inductances, mutual inductance and the number of turns of each stator winding (*Nas*, *Nbs* and *Ncs*), i.e. $\boldsymbol{X} = [rs,\ rr,\ L1r,\ L1s,\ Lm,\ Nas,\ Nbs,\ Ncs]$. It is worth mentioning that values of all the details required for the GA are the same as the default settings of a GA solver in Matlab (R2017b).

4. Results and discussion

The suggested framework for open-circuit fault diagnosis has been validated in the Matlab/Simulink environment using the parameters of an induction motor, which are presented in Table 1 [14].

Table 1. Three-phase induction motor parameters [14]

Parameters	**Values**
Output power	5 hp
Rated voltage	460 V
Rated current	4.925 A
Frequency	60 Hz
Power factor	0.89
Number of poles	4
Moment of inertia (J)	0.025 kg·m^2
Stator resistance (rs)	1.115 Ω
Rotor resistance (rr)	1.083 Ω
Stator inductance ($L1s$)	2.9868 mH
Rotor inductance ($L1r$)	2.9868 mH
Mutual inductance (Lm)	0.10185 H

The generated three-phase currents from the healthy model at full load operation are shown in Fig. 3. The healthy currents are balanced since the healthy model was operated by balance supply voltages.

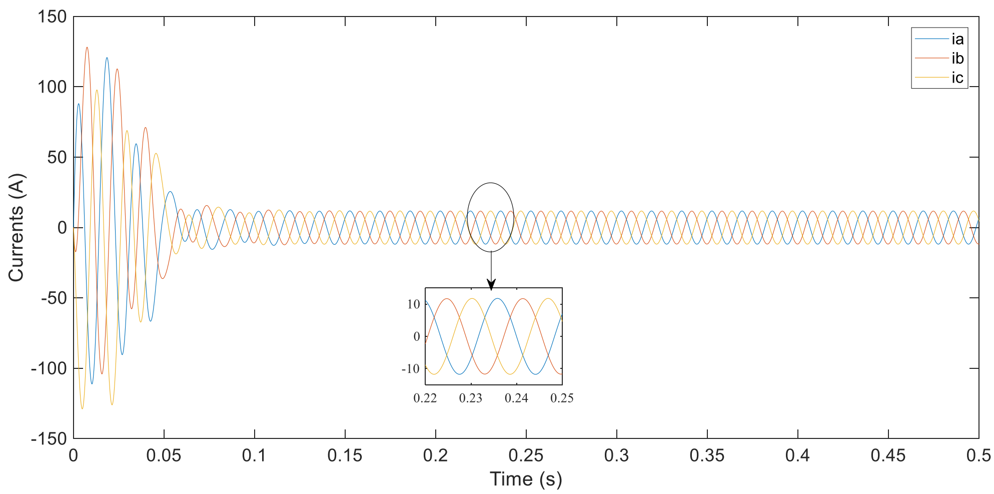

Fig. 3. Three-phase current of the healthy induction motor model

However, the faulty machine with an open-circuit fault has unbalanced currents, as it appears in Fig. 4 for the case when phase “a” was opened at 0.05 s. Once the fault occurs, the healthy

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phases (phase "*b*" and phase "*c*") drawn large magnitude with 180°out while the open circuited phase (phase "*a*") has almost zero current. Therefore, excessive heat will be generated in the heathy phases and that could lead to motor damage unless the fault is detected and isolated from the power source.

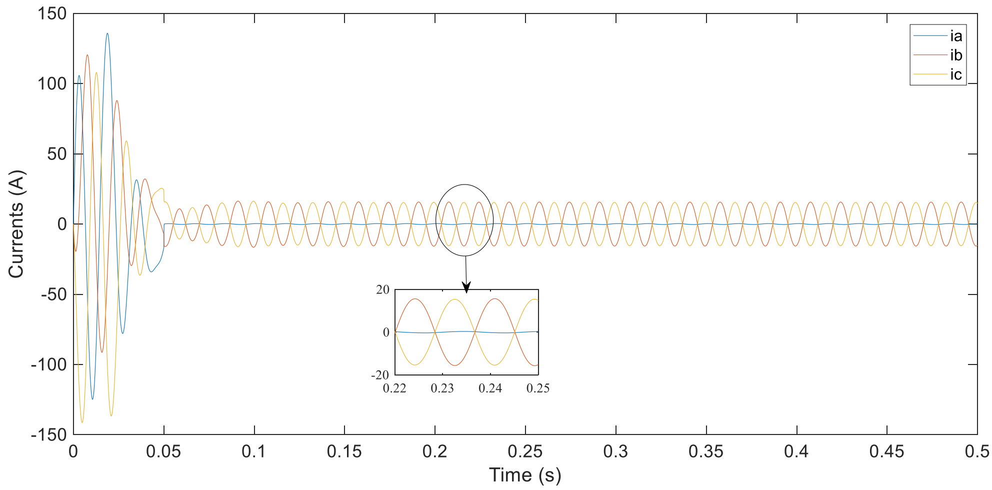

Fig. 4. Three-phase current of induction motor when phase "*a*" opened at 0.05 s

Moreover, the fault has an impact on the speed and the electromagnetic torque of the machine. Fig. 5 illustrates the difference between the electromagnetic torque of the healthy and faulty motor. While the torque curve of the healthy machine is smooth, the faulty machine has a noticeable

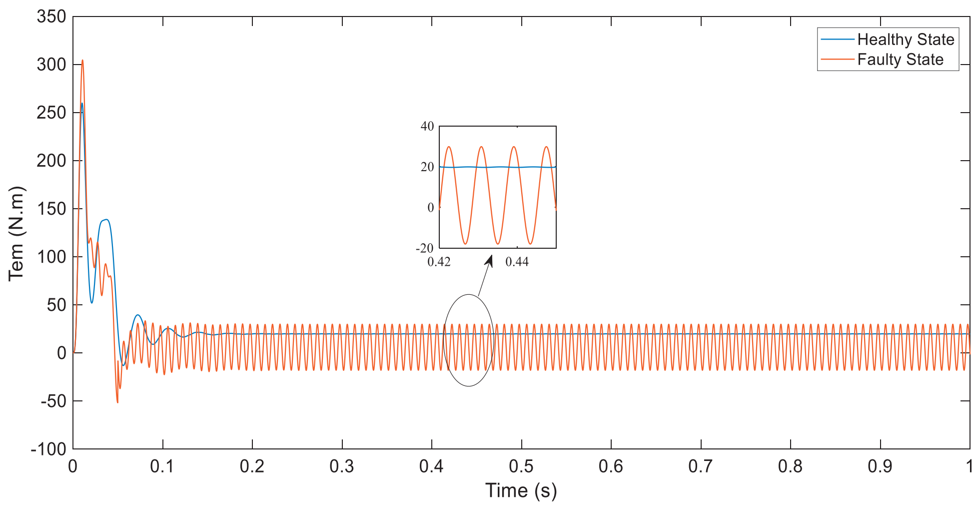

Fig. 5. Electromagnetic torque of healthy and faulty induction motor

magnitude of ripple in its torque curve. Therefore, the average torque of the faulty machine is higher.

The per unit speed (the rotor speed over the based speed) of the healthy and faulty machine is shown in Fig. 6. The effect of open-circuit fault being evidence on the speed curve as the magnitude of ripple is high in the faulty curve.

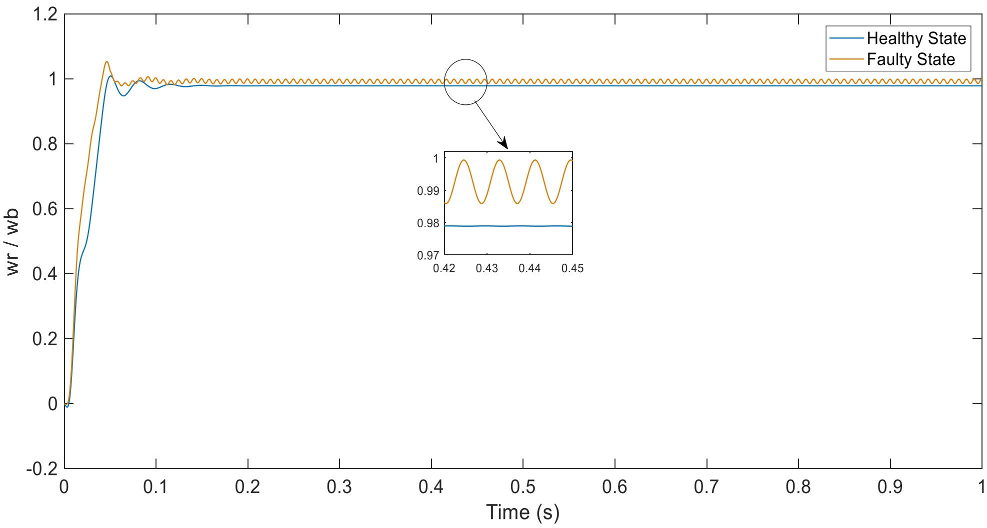

Fig. 6. Per unit speed of healthy and faulty induction motor

The effect of an open-circuit fault on the basic parameters (*L*1*s*, *L*1*r*, *Lm*, *rs* and *rr*) and the number of turns (*Nas*, *Nbs* and *Ncs*) are demonstrated in Figs. 9 to Fig. 12. As suggested in Fig. 1, tracking the behaviour of those parameters is needed to diagnose this fault. It appears that due to the presence of an open-circuit fault, the parameters deviate from their initial values. Table 2 illustrates the percentage of deviation for each parameter for the case when the induction motor was operated at 30% load level and phase "*a*" opened at 0.05 s. The parameters were estimated by a GA, which has the objective of minimizing the sum square of errors between the actual faulty currents at 30% load level and the healthy model currents at 100% load level. It is valuable to mention that the GA was used to estimate the basic parameters firstly and then estimate the number of turns. In addition, the maximum and minimum limits of each parameter were set equal to ±50% from their initial values. This is to speed up the estimation process, which should be stopped when the function tolerance equals 1e-3.

It can be notice in Table 2 that the initial values for the number of turns (*Nas*, *Nbs*, and *Ncs*) and *Ns* are suggested to be one, i.e. the normalized values are used because of the difficulty of estimating the actual values for the number of turns at each phase.

A GA starts from the initial parameters' values and iterates to find the corresponding values of the faulty parameters that are responsible for changing the full load healthy model currents to be in matching with the actual faulty currents, i.e. to minimize the errors between the actual and healthy model currents. For example, Fig. 7 shows the comparison between the actual faulty current and the healthy model current of phase "*a*" before the estimation process and they are

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Table 2. Estimated parameters when phase "*a*" opens

Original Values	**Estimated parameters**	**Percentage of deviation**
$L1r = 0.0029868$ H	$L1r = 0.0020374$ H	–31.78%
$L1s = 0.0029868$ H	$L1s = 0.0038734$ H	29.68%
$Lm = 0.1019$ H	$Lm = 0.10619$ H	4.21%
$Rr = 1.08\ \Omega$	$Rr = 1.1142\ \Omega$	3.166%
$Rs = 1.115\ \Omega$	$Rs = 0.88548\ \Omega$	–20.58%
$Nas = 1$	$Nas = 1.1059$	10.59%
$Nbs = 1$	$Nbs = 0.9086$	–9.14%
$Ncs = 1$	$Ncs = 0.99651$	–0.34%

obviously different. After the estimation, the healthy model currents are well tuned with the actual three-phase faulty current as it is demonstrated for the phase "*a*" current in Fig. 8. Hence, the signals matching confirm the successful use of a GA in the estimation of the corresponding faulty parameters.

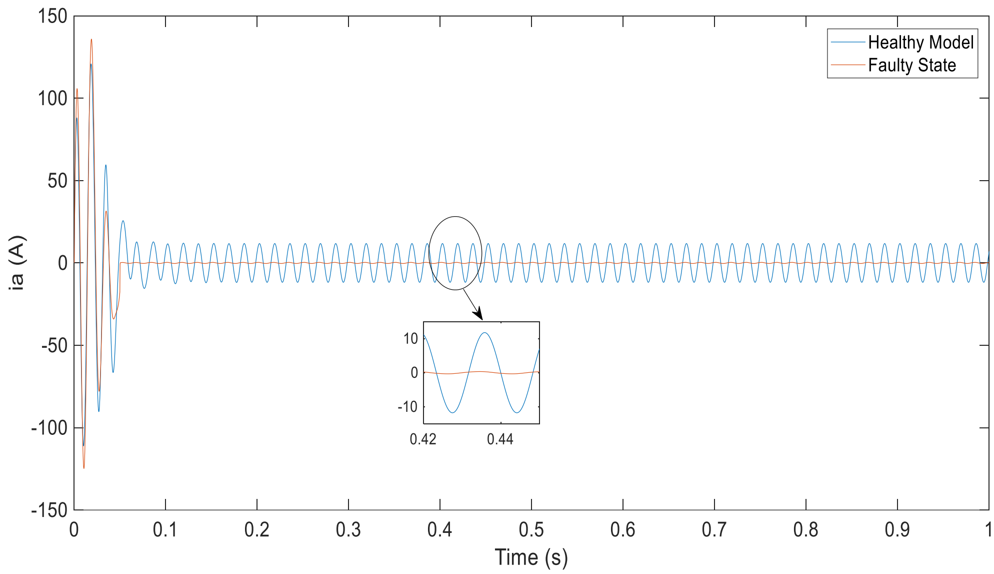

Fig. 7. Comparison between faulty and healthy ia (before estimation)

The process was repeated considering the fault occurs at phase "*b*" and phase "*c*". The results of all cases are summarized in the following figures. Fig. 9 illustrates the corresponding effect of an open-circuit fault on the stator and rotor inductances. They deviate from their original values such that an increment from the original in one parameter is in front of decrement in the other.

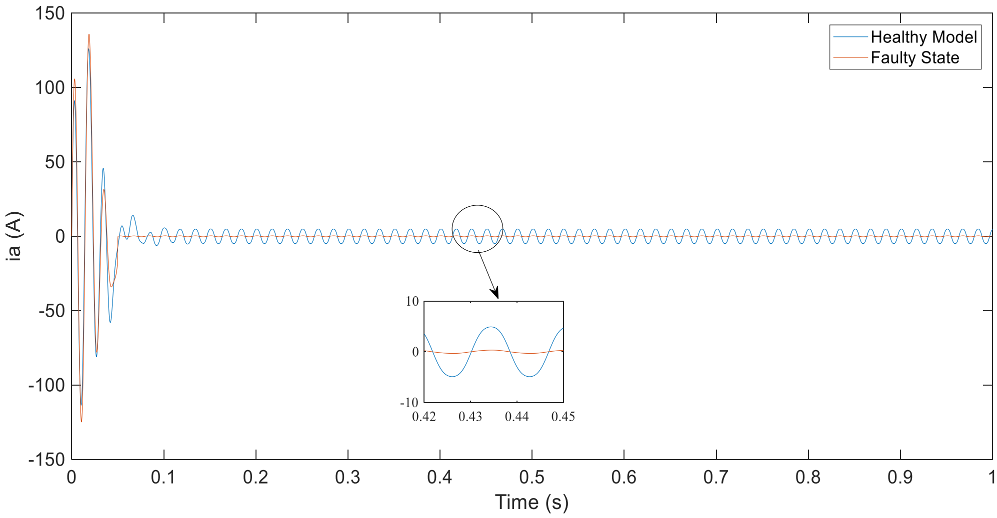

Fig. 8. Comparison between faulty and healthy ia (after estimation)

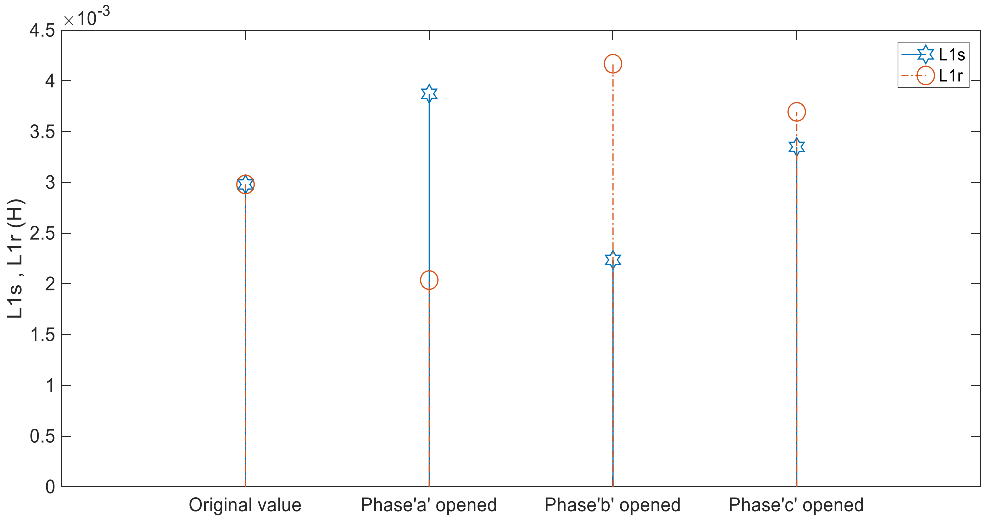

Fig. 9. Deviations from the original value of leakage inductances ($L1s$ and $L1r$) under open-circuit fault

While the estimated mutual inductance for the three faulty cases has a slightly decreasing change from the initial healthy value, as shown in Fig. 10.

The estimated variations of rotor and stator resistances with respect to an open-circuit fault are displayed in Fig. 11. The presence of fault changes the initial healthy value of rotor resistance to another slightly higher value. Nevertheless, the impact of an open-circuit fault on the rotor resistance is inconsiderable in comparison with the stator resistance variation. The stator resistance is markedly decreased compared to its original value because of the occurrence of an open-circuit

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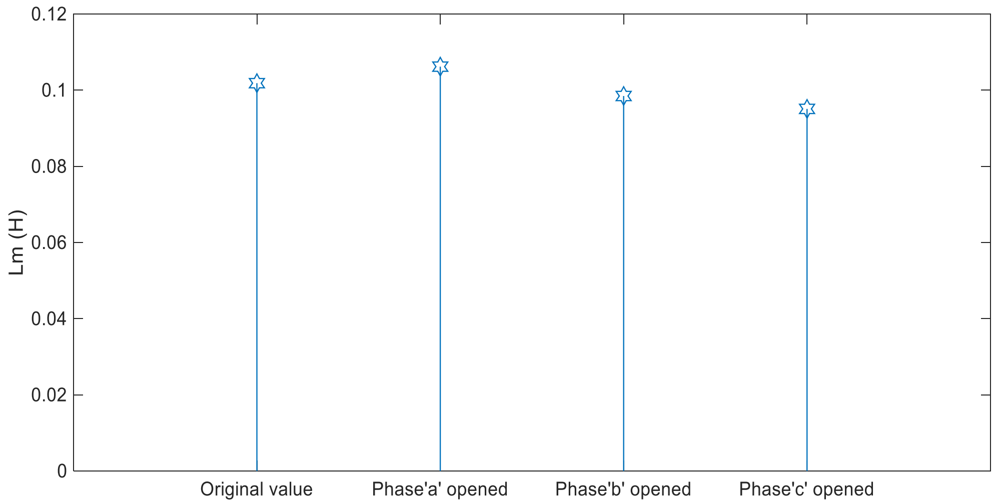

Fig. 10. Deviation from the original value of mutual inductance under open-circuit fault

fault. The decrement in the stator resistance is a result of the high magnitude of currents that are driven by the other remaining healthy phases when one phase is an open- circuit.

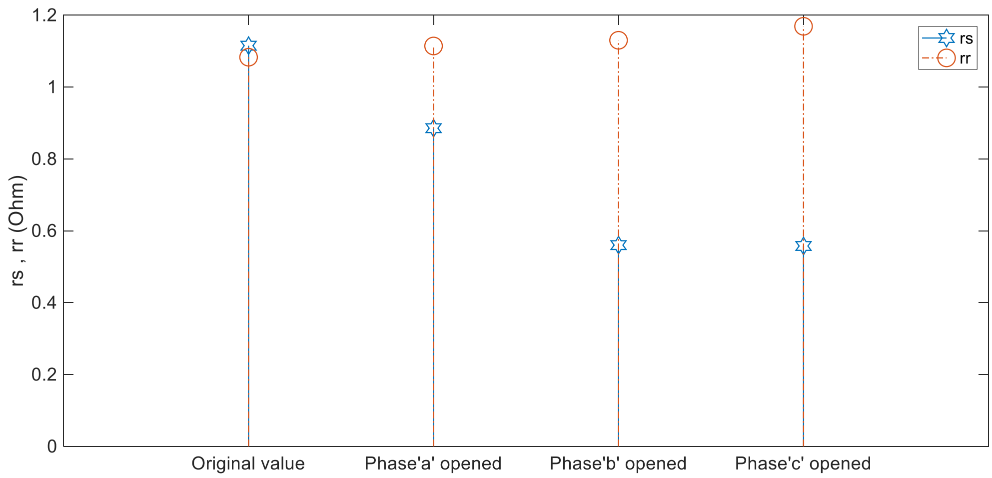

Fig. 11. Deviations from the original values of rotor and stator resistances under open-circuit fault

Fig. 12 shows the estimated behaviour of the number of turns (*Nas*, *Nbs* and *Ncs*) when the open-circuit fault happens. Those parameters have initial values equal to one, which is set to be general for all induction motor sizes. As with the basic parameters, the number of turns also deviate from their initial values due to the presence of an open-circuit fault. The variations of those parameters as shown in Fig. 12 depend on the location of an open-circuit fault. Hence, the equivalent parameter for the number of turns shows a considerable increase compared to the original value when the fault occurs in the corresponding phase, while, the other equivalent parameters for the number of turns in the healthy phases show a slight change. Hence, it is easier to detect the fault and make a trustable decision about the location of an open-circuit fault by following the variations of those parameters.

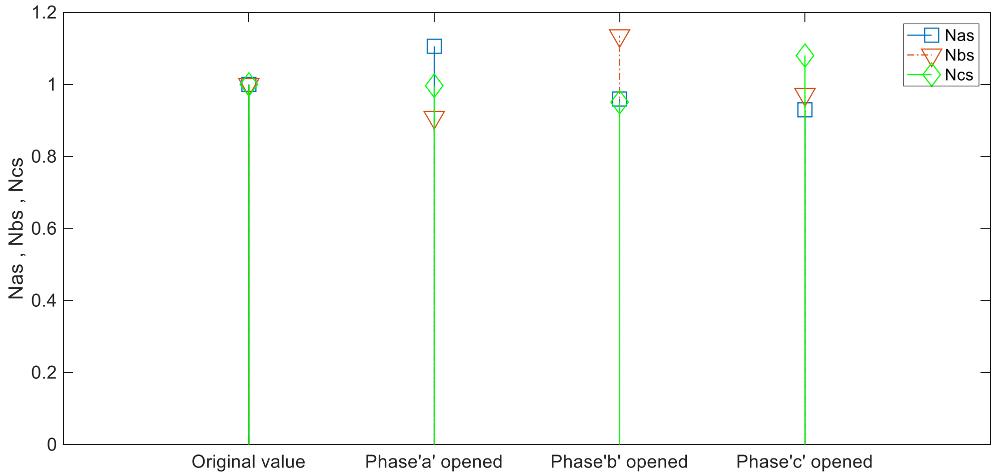

Fig. 12. Deviations from the original values of number of turn's parameters under open-circuit fault

5. Conclusion

This paper presents an approach to diagnosing an open-circuit fault in an induction motor, since that fault leads to severely unbalanced voltages and excessive heating that can absolutely damage the motor. The suggested diagnostic method depends on tracking the behaviour of induction motor parameters to detect and locate an open-circuit fault. The equivalent behaviour of the basic parameters and the number of stator winding turn's parameters are estimated by using model-based technique with the assistance of a genetic algorithm. The simulation results demonstrate the effect of an open-circuit fault on the operation of an induction motor. Consecutively that effect reflects on the induction motor parameters, which considerably deviate from their initial healthy values when the fault occurs. Moreover, the results recommend using the number of turn parameters as an identifier of the presence of an open-circuit fault.

References

[1] Sobański P., Orłowska-Kowalska T., *Detection of single and multiple IGBTs open-circuit faults in a field-oriented controlled induction motor drive*, Archives of Electrical Engineering, vol. 66, no. 1, pp. 89–104 (2017).

[2] Khalid Abdulhassan, Adel Obed, Sadiq Hassan, *Stator Faults Diagnosis and Protection in 3-Phase Induction Motor Based on Wavelet Theory*, Journal of Engineering, vol. 23, no. 11, pp. 130–149 (2017).

[3] Arkan M., Perovic D.K., Unsworth P., *Online stator fault diagnosis in induction motors*, IEE Proceedings-Electric Power Application, vol. 148, no. 6, pp. 537–547 (2001).

[4] M'hamed Drif, Heonyoung Kim, Jongwan Kim, Sang Bin Lee, Antonio J. Marques Cardoso, *Active and Reactive Power Spectra-Based Detection and Separation of Rotor Faults and Low-Frequency Load Torque Oscillations*, IEEE Transactions on Industry Applications, vol. 53, no. 3, pp. 2702-2710 (2017).

[5] Ali Karimabadi, Mohammad Ebrahim Hajiabadi, Ebadollah Kamyab, *Prioritization approach for circuit breakers to equip with condition monitoring devices*, Archives of Electrical Engineering, vol. 69, no. 2, pp. 403–422 (2020).

[6] Subhasis Nandi, Hamid A. Toliyad, Xiaodong Li, *Condition Monitoring and Fault Diagnosis of Electrical Motors – A Review*, IEEE Transactions on Energy Conversion, vol. 20, no. 4, pp. 719-729 (2005).

[7] Fernando F.J.T.E., Silva A.M., Almeida A.T., *Single-Phasing Protection of Line-Operated Motors of Different Efficiency Classes*, IEEE Transactions on Industry Applications, pp. 1–14 (2018), DOI: 10.1109/TIA.2018.2797884.

[8] Mohamoud Omran A. Alamyal, *Evaluation of Stochastic Optimisation Algorithms for Induction Machine Winding Fault Identification*, PhD Thesis, School of Electrical and Electronic Engineering, Newcastle University, United Kingdom (2012).

[9] Mahadev Kokare, Chandle J.O., Rahul Kavathe, Mayur Deokar, *Fuzzy Logic Based Fault Diagnosis of Induction Motor Using MATLAB*, International Journal of Research and Scientific Innovation, vol. V, iss. Vl, pp. 149–152 (2018).

[10] Rama Hammo, *Faults Identification in Three-Phase Induction Motors Using Support Vector Machines*, Master of Technology Management Plan II Graduate Projects, Browling Green State University, Ohio (2014).

[11] Arkan M., Kostic-perovic D., Unsworth P.J., *Modelling and simulation of induction motors with inter-turn faults for diagnostics*, Electric Power Systems Research, vol. 75, pp. 57–66 (2005).

[12] Ding S.X., *Model-based Fault Diagnosis Techniques*, Springer-Verlag (2008).

[13] Ladoukakis O., Tsitmidelis S., Ktena A., *A New Genetic Algorithm for Motor Parameter Estimation*, Proceedings of the 10th WSEAS International Conference on SYSTEMS, pp. 555–558 (2006).

[14] Hamid Reza Mohammadi, Ali Akvahan, *Parameter Estimation of Three-Phase Induction Motor Using Hybrid of Genetic Algorithm and Particle Swarm Optimization*, Journal of Engineering, pp. 1–6 (2014), DOI: 10.1155/2014/148204.

[15] Król K., Machczyński W., *Optimization of electric and magnetic field intensities in proximity of power lines using genetic and particle swarm algorithms*, Archives of Electrical Engineering, vol. 67, no. 4, pp. 829–843 (2018).

[16] Vasconcelos J.A., Ramírez J.A., Takahashi R.H.C., Saldanha R.R., *Improvements in Genetic Algorithms*, IEEE Transactions on Magnetics, vol. 37, no. 5, pp. 3414–3417 (2001).