Original article

An efficient, simplified multiple-coupled circuit model of the induction motor aimed to simulate different types of stator faults

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Abstract

This paper proposes an original simplified model aimed to simulate, an easy way, inter turns short circuit fault, phase to phase fault and phase to ground fault. In this model, the stator is considered as six magnetically coupled windings and the rotor as three not magnetically coupled R–L circuits. The paper also presents the star- and delta-connected stator configurations of the simplified model. However, the proposed simplified model is suitable only for steady-state operation. The performance of the simplified model is first verified by a comparison between the simulated current of the multiple-coupled model and the simplified model. Then, since the stator faults have an impact on the symmetrical components of the stator current, this paper uses these components to validate the behavior of the simplified model by simulation and experimentally using a 1.1 kW motor. In addition, simulated results of the simplified model for a 110kW motor are presented in order to generalize the use of the proposed model to larger motors.

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Keywords: Fault diagnosis; Inter turns short circuit fault; Phase to phase fault; Phase to ground fault; Symmetrical components

1. Introduction

The IM is subjected to variety of undesirable stresses which may lead to different types of faults. Several reported works show that 30% at 40% of IM failures are due stator windings breakdown [23]. Therefore, stator fault diagnosis has received intense research interest [3,4,6,8,10,14–17,23,27,28]. To study the behavior of the motor under fault conditions, it is very difficult to create a real fault into the motor and monitor its evolution. This is because the fault can be dangerous for the motor and can lead to the destruction of the machine.

For this reason the modeling of the IM remains always an effective tool to predict the behavior of the IM under fault conditions [15]. Thus, an accurate and simple model is useful for studying the behavior of the motor under different stator fault conditions. Consequently, intensive interest in fault simulation studies has provided a literature very rich in numerous developed models which range from the simplest T-equivalent circuit models of the machine to more sophisticated ones such as multiple-coupled circuit (MCC) models [2,5,18,19,22,26], magnetic equivalent circuit

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(MEC) models [12,13,20,24,25] and finite-element method (FEM) models [1,9,11,21,29–32]. For more details about these models, we present an outline of their conception.

The MCC model is widely used to simulate and study the fault conditions of the IM [14,18,19]. The first developed MCC model of the IM is presented in [19]. For a MCC model the IM can be represented by the classic voltage equations of the stator (with shorted turns) and the rotor as well as the torque equation (mechanical equation) in the (abc) frame. These equations are represented as function of the resistances, inductances and mutual inductances. The conception of this model is mainly based on the basic geometry and windings layout of the arbitrary phases machine. In such a model, parameters (particularly the mutual inductances between stator and rotor windings) are considered to be time-varying and can be evaluated in real time, while secondary parameters such as end-turn effect, leakage inductances are pre-calculated and treated as constants. These machine inductances are conveniently calculated by means of winding function. According to winding function theory, the mutual inductance between any two windings “i” and “j” in any electric machine can be computed by Eq. (1) (assuming that permeance of iron is infinite) [19]

\[
L_{ij} = \frac{\mu_0 \cdot l \cdot r}{g} \int_0^{2\pi} N_i(\varphi, \theta) \cdot N_j(\varphi, \theta) \cdot d\theta
\]

where \( \varphi \) is the angular position of the rotor with respect to some stator reference, \( \theta \) is a particular angular position along the stator inner surface, \( g \) is termed the gap function due to the assumption of uniform air gap. The quantity “\( l \)” is the length of stack and “\( r \)” is the average radius of the air gap. The term \( N_i(\varphi, \theta) \) is called the winding function and represents, in effect, the MMF distribution along the air gap for a unit current flowing in winding \( i \). The self inductance terms can be calculated by merely setting \( i = j \) [19].

Moreover, with the aim of simplifying the MCC model, a reference frame transformation theory had been widely applied to the MCC model as it is shown in several papers [2,26]. In fact, the expressions of the voltage equations of the healthy IM and the faulty turns as well as the torque equation can be transformed from the (abc) frame to the stationary reference frame (dq), where the machine equations are therefore expressed in complex (dq) variables to represent a transient model suitable for simulating an inter turns short circuit (ITSC) fault in one phase.

Concerning the MEC model, this type of model is based on a detailed magnetic modeling of the machine. The magnetic field distribution within the motor is used to evaluate the performance of the motor since it contains full information on the stator, rotor and mechanical parts of the motor. Based on this idea, a magnetic equivalent circuit (MEC) model has been proposed in several reported works [12,13,24,25]. Thus, each stator and rotor slot can be modeled as a simplified magnetic equivalent circuit composed by closed loop paths containing a magnetic flux (\( \Phi \)), magnetic reluctance (\( R \)) and magneto-motive forces mmfs (\( F \)). The resolution of this circuit is conventionally based on Ohm’s and Kirchoff’s laws for magnetic and electric circuits. The complete MEC model of the IM is therefore assembled such that every tooth on the stator is coupled to every tooth on the rotor, and vice versa as explained in [24]. The MEC model needs shorter computation time compared with the FEM.

In fact, Finite Element Method (FEM) is a useful technique for the analysis of any electromagnetic system [1]. This method is very accurate and flexible but, due to complexity, the dynamic modeling of an induction machine is quite complicated and requires too much computational time. The FEM-based programs can compute the magnetic field distribution in any electrical machine, and from this, all the parameters and characteristics of the machine can be easily obtained, such as the magnetic flux density, inductances, electromagnetic torque and even the current evaluation [9,11,21,31]. The FEM is also used in recent works for modeling and studying the PM motor under inter turns short circuit fault [32] and to identify their parameters as shown in [29,30].

According to the latest approaches to IM modeling, as discussed above, it can be noted that suitable models to simulate and analyze multiple stator faults of the motor with a satisfactory accuracy do not yet exist. For this reason, significant efforts are employed in this work to develop a simple and efficient model able to simulate different types of stator faults which are: ITSC, phase to phase and single phase to ground faults. In this paper, a MCC model has been simplified using Simulink/Matlab. The classical MCC model is transformed in order to be a tool handy to use and to create in an easy way any desirable stator fault such as inter turns short circuit, phase to phase, and phase to ground faults, just by connecting the two desired points where the fault is established in the sub-model bloc of Simulink. Thus, the proposed simplified model characterizes the originality of this paper.
2. Description of the model

2.1. Faulty electromagnetic coupled model

A conventional MCC model of a three-phase IM is mutually coupled with all the other windings. In this paper, the modeling of the machine adopts the following assumptions:

- the air gap is uniform and the electromotive force are sinusoidally distributed around the air gap,
- the effects of the stator slots are neglected,
- the coils are concentric type for the two studied motors,
- magnetic saturation, eddy current and hysteresis effects are neglected,
- the structure of the machine is symmetric (no inherent asymmetries),
- the fault current is due to the start of carbonizing of the insulation, creating a low magnitude of the fault current.

Considering a machine with a star-connected (Y) stator, where A, B, and C denote the three stator phases and a, b, and c represent the three rotor phases which are also star-connected. Therefore, to take into account an ITSC fault in phase A, it is convenient to divide the phase A of the faulty model into two inductances ($L_{A1}$ and $L_{A2}$) [5,22]. Consequently, the stator is thus formed by four windings ($L_{A1}$, $L_{A2}$, $L_B$ and $L_C$). To simplify the notation, the four stator windings are noted ($L_1$, $L_2$, $L_3$ and $L_4$) as it is shown in Fig. 1. The inductance $L_2$ is composed by $N_2$ turns (shorted turns) where the short circuit is occurred through a resistance $R_d$ (to limit the shorted current). The inductance $L_1$ is composed by $N_1$ healthy turns. Note that $N$ is the total healthy turns per healthy phase.

For a considered fault in phase A, according to Kirchoff’s law, the voltage equations of the IM can be expressed as follows:

$$[V] = [R][i] + \frac{d}{dt}([L] \cdot [i])$$

(2)

where

$$[V] = \begin{bmatrix} V_{A1} & V_{A2} & V_B & V_C & 0 & 0 \\ \end{bmatrix}^T : \text{squirrel cage motor}$$

(3)

$$[i] = \begin{bmatrix} i_{A1} & i_{A2} & i_B & i_C & i_a & i_b & i_c \end{bmatrix}^T$$

(4)
\[
\begin{bmatrix}
xa \cdot Rs & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & (1 - xa)Rs & 0 & 0 & 0 & 0 \\
0 & 0 & Rs & 0 & 0 & 0 \\
0 & 0 & 0 & Rs & 0 & 0 \\
0 & 0 & 0 & 0 & Rr & 0 \\
0 & 0 & 0 & 0 & 0 & Rr
\end{bmatrix}
\] (5)

\[
\begin{bmatrix}
L_{11} & L_{12} & L_{13} & L_{14} & L_{1a} & L_{1b} & L_{1c} \\
L_{21} & L_{22} & L_{23} & L_{24} & L_{2a} & L_{2b} & L_{2c} \\
L_{31} & L_{32} & L_{33} & L_{34} & L_{3a} & L_{3b} & L_{3c} \\
L_{41} & L_{42} & L_{43} & L_{44} & L_{4a} & L_{4b} & L_{4c} \\
L_{a1} & L_{a2} & L_{a3} & L_{a4} & L_{a} & L_{ab} & L_{ac} \\
L_{b1} & L_{b2} & L_{b3} & L_{b4} & L_{ab} & L_{b} & L_{bc} \\
L_{c1} & L_{c2} & L_{c3} & L_{c4} & L_{ac} & L_{bc} & L_{c}
\end{bmatrix}
\] (6)

By defining

\[
L_1 = xa^2 \cdot L_s + xa^2(1 - xa) \cdot \frac{fts}{5} \cdot L_s
\] (7)

\[
L_2 = (1 - xa)^2 \cdot L_s + xa(1 - xa)^2 \cdot \frac{fts}{5} \cdot L_s
\] (8)

\[
L_3 = L_4 = L_s
\] (9)

\[
L_{a} = L_{b} = L_{c} = L_r
\] (10)

For the computation of the mutual inductance it should take into account the mutual leakages, as follows:

\[
L_{\alpha\beta} = \sqrt{L_{a\text{Mut}} \cdot L_{\beta\text{Mut}}} \cdot (\cos \theta) \text{ with } \alpha \text{ or } \beta = 1, 2, 3, a, b \text{ or } c
\]

and \(L_{a\text{Mut}} = L_{a}(1 - fts)\) with \(\varepsilon = s, \ r \text{ or } sr\) (examples: \(L_{3\text{Mut}} = L_{s}(1 - fts)\))

or \(L_{1\text{Mut}} = xa^2 \cdot L_s(1 - fts)\).

\[
L_{12} = xa(1 - xa)L_s \cdot \left(1 - \frac{fts}{10}\right)
\] (11)

**Remark:** The second term of Eqs. (7) and (8) taking into account the leakage between \(L_1 \text{ and } L_2\) (\(fts/10\) in Eq. (11)) must be introduced in order to keeping the same value of the global inductance \((L_a)\) of the first phase.

\[
L_{13} = L_{14} = \frac{-xa \cdot L_s}{2} (1 - fts)
\] (12)

\[
L_{23} = L_{24} = \frac{-(1 - xa) \cdot L_s}{2} (1 - fts)
\] (13)

\[
L_{34} = \frac{-L_s}{2} (1 - fts)
\] (14)

\[
L_{1a} = \sqrt{L_1 \cdot L_r} (1 - fts) \cdot \cos (\theta)
\] (15)
\[ L_{1b} = \sqrt{L_1 \cdot L_{fr}(1 - ftsr)} \cdot \cos \left( \theta + \frac{2\pi}{3} \right) \]  

(16)

\[ L_{1c} = \sqrt{L_1 \cdot L_{fr}(1 - ftsr)} \cdot \cos \left( \theta - \frac{2\pi}{3} \right) \]  

(17)

\[ L_{2a} = \sqrt{L_2 \cdot L_{fr}(1 - ftsr)} \cdot \cos (\theta) \]  

(18)

\[ L_{2b} = \sqrt{L_2 \cdot L_{fr}(1 - ftsr)} \cdot \cos \left( \theta + \frac{2\pi}{3} \right) \]  

(19)

\[ L_{2c} = \sqrt{L_2 \cdot L_{fr}(1 - ftsr)} \cdot \cos \left( \theta - \frac{2\pi}{3} \right) \]  

(20)

\[ L_{3a} = L_{4b} = \sqrt{L_s \cdot L_{fr}(1 - ftsr)} \cdot \cos \left( \theta - \frac{2\pi}{3} \right) \]  

(21)

\[ L_{3b} = L_{4c} = \sqrt{L_s \cdot L_{fr}(1 - ftsr)} \cdot \cos (\theta) \]  

(22)

\[ L_{3c} = L_{4d} = \sqrt{L_s \cdot L_{fr}(1 - ftsr)} \cdot \cos \left( \theta + \frac{2\pi}{3} \right) \]  

(23)

\[ L_{ab} = L_{ac} = L_{bc} = \frac{-L_{fr}}{2}(1 - ftr) \]  

(24)

with

\[ xa = \frac{N1}{N} \]  

(25)

\( xa \) is the healthy part of the winding of phase A; \( N1 \) is the healthy turns and \( N \) is the total turns per phase; \( R_s \) and \( R_r \) are the stator and rotor resistances respectively; \( L_s \) and \( L_r \) are the self inductances of the stator and rotor windings respectively; \( L_{ss'} \) is the mutual inductance between two stator windings, with \( s \) or \( s' = 1, 2, 3 \) or 4, \( L_{rr'} \) is the mutual inductance between two rotor windings, with \( r \) or \( r' = a, b \) or \( c \), \( L_{sr} \) is the mutual inductance between the stator and rotor windings; \( L_{rs} \) is the mutual inductance between the rotor and the stator windings; \( fts, ftr \), and \( ftsr \) are stator/stator, rotor/rotor and stator/rotor percentages of leakages respectively. A small leakage flux is considered for the coils of the same winding between \( L_1 \) and \( L_2 \). Ten percent of stator/stator leakage \((fts/10)\) has been considered in this work.

### 2.2. Resolution of the model

The resolution of the equations system (2) allows determination of the values of different currents flowing in each stator phase. Two other equations ((27) and (29)) which represent the sum of the stator currents and rotor currents, should be added to this system of equations. Thus, it is clear that it is impossible to solve the latter system, since the number of proposed equations exceeds the number of unknown variables. In addition to the seven unknown currents into vector \([i]\), the new voltages \(V_B^c\) and \(V_C^c\) into vector \([V]\) are also unknown because the potential of the neutral point changes with the occurrence of a fault.

To resolve the system (2), it is therefore advantageous to consider five loops flowing by the fictive currents \( J_1, J_2, J_3, J_4 \) and \( J_5 \) and using the line to line voltages as shown in Fig. 2. So, the new equations system can be written as given in (26).

The different elements of the new voltage vector \([U]\) are now well defined. It is composed of line to line supply voltages \(U_{AB}\) (for the loop of \( J_1 \)), \(U_{BC}\) (for the loop of \( J_2 \)), zero for the loop \( J_3 \), and zero for the two loops \( J_4 \) and \( J_5 \) of the rotor (squirrel cage rotor). Thus, this approach involves eight unknown currents \((i_{A1}, i_{A2}, i_B, i_C, i_a, i_b, i_c \text{ and } i_d)\) (where \( id \) is the fault current through the resistance \( Rd \) defined previously). To define these eight currents, eight equations are required, which are five equations of voltage concerning the five loops \( (J_1, J_2, J_3, J_4 \text{ and } J_5) \) represented
by Eq. (26), and three current equations introduced by (27), (28) and (29). As a result, the proposed system can be therefore solved.

\[ [U] = [R][J] + \frac{d([L] : [J])}{dt} \]  \hspace{1cm} (26)

\[ \tilde{i}_{A1} + \tilde{i}_{B} + \tilde{i}_{C} = 0 \]  \hspace{1cm} (27)

\[ \tilde{i}_{A1} = \tilde{i}_{A2} + \tilde{i}_{d} \]  \hspace{1cm} (28)

\[ \tilde{i}_{a} + \tilde{i}_{b} + \tilde{i}_{c} = 0 \]  \hspace{1cm} (29)

with \([U] = [U_{AB} \ U_{BC} \ 0 \ 0 \ 0]^T\); \([J] = [J_1 \ J_2 \ J_3 \ J_4 \ J_5]^T\); \([R] \) is the new resistance matrix and \([L] \) is the new inductance matrix.

The real currents flowing through the stator and rotor phases as well as the faulty current \(i_d\) are determined by the following relationships of (30):

\[ \tilde{i}_{A1} = J_1; \quad \tilde{i}_{B} = -J_2; \quad \tilde{i}_{C} = J_2 - J_1; \quad \tilde{i}_{d} = J_3; \quad \tilde{i}_{a} = J_4; \quad \tilde{i}_{b} = J_5 - J_4; \quad \tilde{i}_{c} = -J_5 \]  \hspace{1cm} (30)

Although this model can be solved, it remains rather complicated and presents many drawbacks. In fact, in the case of a fault in only one phase, the model seems to be complicated since the inductance matrix depends on the rotor angle position. So, if more faults on other phases are considered the matrix becomes more and more complicated and thus, the model requires a huge time to be simulated. Furthermore, this faulty model is not flexible enough to take into account and simulate multiple simultaneous faults, and consequently, appropriate models should be developed for each fault. Obviously all these drawbacks seem to be a major reason to simplify the model. The suggested simplified model is therefore conceived in steady-state operating, and a dynamic model is not therefore useful because we are interested in the machine behavior under fault conditions only in steady-state operating.

2.3. The proposed simplified model

In steady state, the per-phase model of the induction machine can be simplified by a four parameters scheme as it is shown in Fig. 3(a). The resistance \(R_1\) represents the stator winding resistance, \(L_{m}\) is the mutual inductance, \(R_1/s\) is the resistance of the rotor, where “s” is the slip of the rotor and \(L_{trs}\) includes the leakage inductances of stator and rotor. Thus, the stator current is the sum of the magnetizing current (flowing through \(L_{m}\)) and the rotor equivalent current (flowing through \(L_{trs} + R_1/s\)) which depends of the torque. In the case of an incipient (in an early stage of appearance) stator fault (Inter turns short-circuits, phase to phase or phase to ground), the common flux can be considered the same as in case of no faults (healthy case), because the flux is forced by the supply voltage. Therefore, in this case the voltage drop across \(R_1\) can be neglected, and the simplified model (per-phase) can be represented in Fig. 3(b). To put the entire
(three phases) machine, Fig. 4 shows the complete scheme including the ability to add stator faults. The scheme of Fig. 4 keeps the same stator coupled inductances as those represented in the scheme of Fig. 2.

Accordingly, the idea of the simplification of the classic complex model of Fig. 2 is inspired by the principle of Fig. 3(b) and the proposed simplified model is therefore represented in Fig. 4. This simplified model is composed of a machine where the stator is considered as multiple electromagnetic coupled circuits not magnetically coupled with the rotor although the stator and the rotor are subjected to the forced common flux. Regarding the rotor, it is composed of three \( R-L \) circuits represented only by the magnetic leakages and the transmitted power as in the steady-state equivalent circuit of the IM (Fig. 3(b)). In this case, different elements of the rotor have no magnetic interaction either between them or with the three stator windings. This proposal simplifies significantly the model and specifically the stator inductance matrix since it becomes independent of the angle position of the rotor and contains only the self coupled stator inductances. Moreover, it is possible to take into account an ITSC fault (or other faults) in the three stator phases without over-complicating the model. Furthermore, this proposed model can be easily achieved by Simulink/Matlab and offers the possibility to simulate the different types of stator fault (ITSC, phase to phase and phase to ground) without changing the configuration of the model for each type of fault.

The stator of the simplified model is implemented in the interface of Simulink as a mutual inductance sub-system block composed of six windings, where each winding is subdivided into two parts. Hence, the stator is viewed as a six magnetically coupled windings \( (L_1, L_2, L_3, L_4, L_5 \) and \( L_6 \)), conceived mainly in order to obtain an access point in each stator winding offering the possibility to create a short circuit between any desirable number of turns of the same phase, or between any two phases or between a phase and the ground with the possibility of using or not a resistance \( R_d \) to limit the fault current. Thus, as it is depicted in Fig. 4, the stator is represented by a block having three inputs.
(for the three-phase supply voltage) and four outputs representing the three intermediate access points and the neutral point. This approach is particularly suitable for the simulation of a variety of stator faults such as an ITSC, phase to phase and phase to ground faults. The expressions of the new inductance and resistance matrices of the stator of this simplified model are now defined as follows:

\[
[R] = \begin{bmatrix}
xa \cdot R_s & 0 & 0 & 0 & 0 & 0 \\
0 & (1 - xa)R_s & 0 & 0 & 0 & 0 \\
0 & 0 & xb \cdot R_s & 0 & 0 & 0 \\
0 & 0 & 0 & (1 - xb)R_s & 0 & 0 \\
0 & 0 & 0 & 0 & xc \cdot R_s & 0 \\
0 & 0 & 0 & 0 & 0 & (1 - xc)R_s
\end{bmatrix}
\] (31)

\[
[L] = \begin{bmatrix}
L_1 & L_{12} & L_{13} & L_{14} & L_{15} & L_{16} \\
L_{12} & L_2 & L_{23} & L_{24} & L_{25} & L_{26} \\
L_{13} & L_{23} & L_3 & L_{34} & L_{35} & L_{36} \\
L_{14} & L_{24} & L_{34} & L_4 & L_{45} & L_{46} \\
L_{15} & L_{25} & L_{35} & L_{45} & L_5 & L_{56} \\
L_{16} & L_{26} & L_{36} & L_{46} & L_{56} & L_6
\end{bmatrix}
\] (32)

In the interface of Simulink, the rotor is however implemented as a Y connected three-phase series \(R-L\) block (resistance and inductance) as it is shown in Fig. 4. The sum of the stator currents as well as the rotor currents is equal to zero in case of a stator with an unconnected neutral, and also in case of the absence of phase to ground fault.

The validation of the simplified model by experiments and by simulation is based essentially on the use of the symmetrical component of the current. These components are also used to study the impact of the different considered stator faults on these components.

The potential advantage of the developed model is its flexibility in achieving any type of stator faults in easy way, just by linking two points on the graphic interface of Simulink.

The other advantage of this model is the possibility of studying the behavior of a star-connected machine as well as a delta-connected (\(\Delta\)) machine under stator faults, just by changing the connection of the three stator and rotor windings on the graphic interface of Simulink. The simplified model with \(\Delta\) connected stator is shown in Fig. 5. The
developed model becomes therefore a tool easily handled to simulate and to study the behavior of the machine under stator fault conditions.

3. Validation of the model

In this section only the validation of the Y configuration is presented since both Y and Δ configurations of the SM have the same behavior, except that, in case of Δ connection the line and the phase currents are not the same.

The validation of the simplified model by experiments and by simulation is based essentially on the use of the symmetrical component of the current. These components are also used to study the impact of the different considered stator faults on these components.

The method of symmetrical components is intensively used for analysis and solves the unbalanced systems [7,10,17]. In this paper, the attention is focused on the behavior of the negative and zero sequences stator current which reveal interesting features making them powerful and reliable indicators of different types of stator faults, as will be thoroughly shown in the followed sections relating to the study of the symmetrical components’ behavior under stator fault conditions in steady state.

The calculation of the symmetrical components \( (I_1, I_2, I_0) \) obtained from a three unbalanced set of the IM currents \( (i_A, i_B, i_C) \) is based on the use of the complex Fortescue’s transformation: We obtain therefore:

Positive sequence component:

\[
I_1 = \frac{1}{3}(i_A + a \cdot i_B + a^2 \cdot i_C)
\]

Negative sequence component:

\[
I_2 = \frac{1}{3}(i_A + a^2 \cdot i_B + a \cdot i_C)
\]

Zero sequence component:

\[
I_0 = \frac{1}{3}(i_A + i_B + i_C)
\]

with \( a = e^{j\pi/3} \) and \( i_A, i_B \) and \( i_C \) are the three stator line currents.

The validation of the behavior of the SM is carried out first by simulation, where the simulated symmetrical components calculated from the SM of Fig. 4 are compared with the symmetrical components calculated from the complete model (CM) of Fig. 2, and then experimentally using data provided by an experimental test bed.

3.1. Validation of simulation

The simulated machine is a 1.1 kW, 2 pole pairs, 230 V/400 V – 50 Hz three-phase squirrel cage induction motor. The three-phase stator windings are Y connected and composed of 464 turns per phase, while the rotor is formed by 28 bars.

The stator electrical parameters of the SM are the same as those of the CM previously described in Section 2, where \( R_s = 9.8 \, \Omega \), \( L_s = 0.33H \) and \( f_{sr} = 2\% \) (stator/stator leakage). The rotor parameters are also the same as those of the CM, where the inductance of the rotor is calculated based on to the steady-state equivalent circuit of the IM represented in Fig. 3(b). The expression of \( L_r \) is then given by (36) where \( (L_m + L_{firs}) \) represents the cyclic inductance.

\[
L_r = \frac{L_m + L_{firs}}{1 + (1 - f_{irs})/2}
\]

with \( L_m = L_s (1 + (1/2)) \). Hence \( L_m = 0.495H \) and \( L_{firs} = 2 \cdot L_m \), since the global stator/rotor leakage inductances are transposed to the rotor, with \( f_{irs} = \text{stator/rotor leakage} = 4\% \) Therefore \( L_{firs} = 0.0396H \).

The parameters of the rotor have the following values: \( R_r = 5.3 \, \Omega \), \( L_r = 0.3588H \), \( f_{irs} = 2\% \) and \( s = 0.045 \) (slip for nominal torque).
Table 1
Comparison between the simulated values of the simplified model (SM) and the complete model (CM) \( \hat{i}_d = 4.24 \text{ A} \).

<table>
<thead>
<tr>
<th>( N_A )</th>
<th>Model</th>
<th>( I_1 ) (A)</th>
<th>( \varphi_1 ) (°)</th>
<th>( I_2 ) (A)</th>
<th>( \varphi_2 ) (°)</th>
<th>( I_0 ) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (1%)</td>
<td>SM</td>
<td>3.809</td>
<td>-39.22</td>
<td>0.015</td>
<td>0.012</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>CM</td>
<td>3.427</td>
<td>-35.9</td>
<td>0.015</td>
<td>-0.005</td>
<td>0</td>
</tr>
<tr>
<td>10 (2%)</td>
<td>SM</td>
<td>3.82</td>
<td>-39.07</td>
<td>0.0305</td>
<td>0.013</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>CM</td>
<td>3.44</td>
<td>-35.75</td>
<td>0.0305</td>
<td>-0.011</td>
<td>0</td>
</tr>
<tr>
<td>50 (10.8%)</td>
<td>SM</td>
<td>3.916</td>
<td>-37.95</td>
<td>0.152</td>
<td>-0.047</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>CM</td>
<td>3.54</td>
<td>-34.6</td>
<td>0.152</td>
<td>-0.055</td>
<td>0</td>
</tr>
<tr>
<td>116 (25%)</td>
<td>SM</td>
<td>4.08</td>
<td>-36.22</td>
<td>0.353</td>
<td>-0.12</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>CM</td>
<td>3.71</td>
<td>-32.84</td>
<td>0.354</td>
<td>-0.129</td>
<td>0</td>
</tr>
</tbody>
</table>

Different ITSC faults in the phase A with different number of shorted turns \( N_2 \) are simulated using both the SM and the CM. For each fault \( I_1, I_2 \) and \( I_0 \) are computed and listed in Table 1 in order to compare the simulated results of the SM with those of the CM. Notice here that the ITSC fault is simulated with fault resistance \( R_d (i_{dms} = 3 \text{ A}) \). According to Table 1, the simulated values obtained by the SM are close to the simulated values obtained by the CM.

Note that \( \hat{x} \) corresponds to the peak value of \( x \) (i.e. \( i_{dms} = 3 \text{ A} \) corresponding to \( \hat{i}_d = 4.24 \text{ A} \)).

On the other hand, the simulated three line currents \( (i_A, i_B, i_C) \) provided by the SM are also tested for the healthy and faulty operation and compared to the three line currents of the CM under fault of 116 (25%) shorted turns in phase A and with a fault current \( i_{dms} \) of 7A \( (R_d=6.2 \Omega) \), as it is illustrated in Fig. 6. The different parameters of the two models SM and CM are as follows:

CM: \( V=231 \text{ V}, R_s=9.8 \Omega, R_f=5.3 \Omega, L_s=0.33H, L_f=0.3588H, f_{ts}=2\%, f_{fr}=4\%, f_r=2\%, n=1431 \text{ rpm}, s=0.046 \).
SM: \( U=400 \text{ V (Y)}, R_s=9.8 \Omega, R_f=5.3 \Omega, L_s=0.33H, f_{ts}=2\%, L_{frs}=0.0396H, n=1431 \text{ rpm}, s=0.046 \).

As can be seen in Fig. 6, the three currents of the SM are in concordance with the three line currents provided by the CM. But it can be also noted that the current of the SM is slightly higher than the current of the CM with an insignificant value. This aspect is due to the fact that the rotor of the SM is powered directly from the supply voltage voltage (see Fig. 3(b)) while the rotor of the CM is supplied by a voltage less then the supply voltage due to the voltage drop across the stator resistance \( R_s \) (see Fig. 3(a)). However, the CM takes into account the voltage drop across the

Fig. 6. Simulated line currents of the SM and the CM under fault of 116 (25%) shorted turns in phase A and with fault current of \( i_{dms} = 7 \text{ A} \).
stator resistance. This difference is larger when the torque increases and/or when the stator resistance is larger (which is the case for low power machines).

According to this meaningful comparison of the simulated results, it can be concluded that the simplified model is able to successfully reproduce the behavior of the IM under fault conditions in steady-state operation and with a satisfactory level of accuracy.

### 3.2. Experimental validation

To verify and confirm the successful application of the proposed model it is necessary to validate the behavior of the SM experimentally. For this purpose, several laboratory tests have been carried out on a motor having the same parameters as those of the simulated machine, except that \( s = 0.043 \). Therefore, the test bed is composed by a 1.1 kW, 2 pole pairs, 230 V/400 V three-phase squirrel cage induction motor as shown in Fig. 7. This motor is coupled to a direct current generator feeding by a variable resistance which is used as a load system. The variation of the resistance leads to the variation of the motor load. The electrical characteristics of the IM are represented in Table 2. The motor is supplied directly by a balanced three-phase sinusoidal voltage source. It is composed by 28 bars in the cage rotor and \( Y \) connected stator windings with 464 turns per phase.

The motor is equipped with specific access points to diverse turns of stator windings in order to achieve different cases of fault as it is shown in Fig. 8. Accordingly, the possible simulated ITSC faults on the IM are on the level of: (18–58–116) turns of the phase \( A \) and (29–58–116) turns of the phase \( B \) from the neutral point of the machine (see Fig. 8).

Table 3 represents the simulated and experimental values of \((I_1, I_2 \text{ and } I_0)\) under different types of faults named fault-1, fault-2 and fault-3. Each fault is performed with a low faulty current \( I_d \) (to study early faults) limited to 4.24 A (3 A rms value). Each fault is defined as follows:

- Fault-1: corresponds to an ITSC fault of 116 shorted turns or (25%) in the phase \( A \).
- Fault-2: corresponds to phase to phase fault with a short circuit between the point of 116 (25%) turns of the phase \( A \) and 58 turns or (12.5%) of the phase \( B \).

<table>
<thead>
<tr>
<th>Supply (V)</th>
<th>( I_{\text{Nref}} ) (A)</th>
<th>( n_N ) (rpm)</th>
<th>( \cos \phi_N ) (P/S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230( \Delta )</td>
<td>4.5</td>
<td>1425</td>
<td>0.82</td>
</tr>
<tr>
<td>400( \gamma )</td>
<td>2.6</td>
<td>1425</td>
<td>0.82</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>–</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>–</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Slots per pole per phase</td>
<td>–</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Type of coiling</td>
<td>–</td>
<td>Concentric coiling</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7. Experimental test bed.
Table 3
Comparison between the simulated and experimental values ($\hat{i}_d = 4.24$ A).

<table>
<thead>
<tr>
<th></th>
<th>Fault-1</th>
<th></th>
<th>Fault-2</th>
<th></th>
<th>Fault-3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_1$ (A)</td>
<td>4.11</td>
<td>4.09</td>
<td>4.2</td>
<td>4.2</td>
<td>4.11</td>
<td>4.05</td>
</tr>
<tr>
<td>$\varphi_1$ (°)</td>
<td>-34.15</td>
<td>-34.3</td>
<td>-33.3</td>
<td>-32.6</td>
<td>-34.23</td>
<td>-34.9</td>
</tr>
<tr>
<td>$I_2$ (A)</td>
<td>0.354</td>
<td>0.293</td>
<td>0.467</td>
<td>0.448</td>
<td>0.3535</td>
<td>0.309</td>
</tr>
<tr>
<td>$\varphi_2$ (°)</td>
<td>-0.129</td>
<td>-6.22</td>
<td>38.2</td>
<td>41.6</td>
<td>-1.22</td>
<td>7.39</td>
</tr>
<tr>
<td>$I_0$ (A)</td>
<td>0</td>
<td>0.006</td>
<td>0</td>
<td>0.024</td>
<td>1.414</td>
<td>1.468</td>
</tr>
</tbody>
</table>

Fault-3: corresponds to phase to ground fault, occurring between point 116 (25%) turns of the phase A and the neutral point of the source. This configuration is adopted because it coincides with the grounding system most used (TT), where the neutral of the source is connected to the earth.

Referring to Table 3, the simulated values of the symmetrical components obtained from the SM are very close to the values of the symmetrical components provided experimentally. This confirms that the model is efficient in successfully reproducing the behavior of the machine under faulty operation. On the other hand, it can be noted that the simulated and experimental values of Table 3 present slight differences due to sensors errors, quantification errors, unbalanced supply network, and the difference between the real speed of the machine and the simulated speed. These differences are also due to the fact that the waveform of the experimental signals are not exactly sinusoidal. Moreover, do not forget that in practice the motor may present small manufacturing asymmetries such as magnetic unbalance, poor eccentricity of the stator and rotor.

According to the experimental validation, the simplified model can be considered as a reliable model to simulate the behavior of the 1.1 kW IM under different stator faults in steady-state conditions.

Based on Table 3, it can be also noted that for ITSC and phase to phase faults, the zero sequence current $I_0$ is theoretically null (near to zero in practice). But, for phase to ground fault (fault-3) the value of $I_0$ has a significant value equal to the third of the faulty current $I_d(1/3 \cdot \hat{i}_d)$. Therefore, the value of $I_0$ can be an efficient index that allows the discrimination between ITSC and phase to ground faults. This result is explained in further detail in Section (4).

In addition, a comparison between simulated line currents of the SM and experimental currents of the 1.1 kW motor under fault conditions are also performed. The example presented in Fig. 9 of a fault of 116 shorted turns (25%) in phase A and a fault current $I_{d_{max}}$ of 7 A ($R_f = 6.2 \Omega$) effectively shows the successful operation of the proposed model and confirms its validation. As it is shown in Fig. 9, simulated and experimental currents have the same shape and are very close. It can be therefore noted that the SM currents are more compatible to the experimental current than to the CM current as it has been shown in Fig. 6. Hence, these aspects prove that the SM is an efficient model able to reproduce the behavior of the IM with satisfactory accuracy and moreover it can be considered as useful tool to study the behavior of the 1.1 kW motor under stator fault conditions in steady-state operation.

![Fig. 8. Configuration of the stator windings of the motor with additional access points.](image-url)
3.3. Generalization of the simplified model for large motor

With the aim of applying the behavior of the simplified model to other types of motor, typically to large induction motors, simulation of the SM considering a 110 kW Leroy Somer (LS) motor is presented in this section. Fig. 10 shows the three line currents of both the SM and the CM under fault of 116 shorted turns (25%) in phase A and a fault current $I_{d_{\text{rms}}}$ of 280 A ($R_d = 0.2 \, \Omega$). The characteristics and the assumption of this used large motor are shown in Table 4. The assumption taken for the type of coils and the configuration of the winding distribution are of a great importance.
Table 4
Characteristics of the 110 kW motor (LS).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated frequency, ( f )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Rated line voltage, ( U )</td>
<td>400 V</td>
</tr>
<tr>
<td>Rated power, ( P_r )</td>
<td>110 kW</td>
</tr>
<tr>
<td>Rated torque, ( T_r )</td>
<td>707 N m</td>
</tr>
<tr>
<td>Nominal speed, ( n_N )</td>
<td>1485 rpm</td>
</tr>
<tr>
<td>Unload current, ( I_u )</td>
<td>201 A</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.83</td>
</tr>
<tr>
<td>Efficiency</td>
<td>95%</td>
</tr>
<tr>
<td>Number of pole pairs, ( p )</td>
<td>2</td>
</tr>
<tr>
<td>Assumption</td>
<td>Concentric coiling</td>
</tr>
</tbody>
</table>

because, if the turns are not situated in the same magnetic axis of the machine, a phase shift in the fault current (\( i_d \)) appears, according to the location of the fault. The electrical parameters of both the CM and SM for a 110 kW motor are as follows:

CM: \( V = 231 \text{ V}, R_s = 0.03 \Omega, R_r = 0.0129 \Omega, L_s = 0.00617 H, L_r = 0.0066252 H, f_s = 1\%, f_{sr} = 3.51\%, f_r = 1\%, n = 1485 \text{ rpm}, s = 0.0101. \)

SM: \( U = 400 \text{ V (Y)}, R_s = 0.03 \Omega, R_r = 0.0129 \Omega, L_s = 0.00617 H, f_s = 1\%, L_{p3} = 0.0006497 H, n = 1485 \text{ rpm}, s = 0.0101. \)

Even for a large motor, the SM presents an efficient performance since the SM currents and the CM currents are very close as is shown in Fig. 10. As in the case of 1.1 kW motor, the SM currents are slightly higher than the CM currents. In addition, the obtained values of \( I_1, \phi_1, I_2, \phi_2 \) and \( I_0 \) calculated from the SM and the CM are very close and their values are as follows:

CM: \( I_1 = 220.4 \text{ A}, \phi_1 = -25.93 \text{ A}, I_2 = 23.33 \text{ A}, \phi_2 = -0.112, I_0 = 0 \text{ A}; \)

SM: \( I_1 = 227.7 \text{ A}, \phi_1 = -28.29 \text{ A}, I_2 = 23.33 \text{ A}, \phi_2 = -0.113, I_0 = 0 \text{ A}; \)

Therefore it can be concluded that the SM is an efficient model able to simulate the behavior of any type of induction motor ranged from small to large motors.

4. Study of the impact of the stator faults on the symmetrical components

After validation of the successful application of the proposed model through simulations and experiments, the SM is therefore considered as an efficient tool useful for studying the behavior of the induction motor under different stator faults. The objective of this section is to extract reliable indicators of ITSC, phase to phase and phase to ground faults, through the study of the behavior of the symmetrical components under fault conditions.

4.1. Study of the impact of phase to phase fault

In order to analyze and understand the behavior of the IM under phase to phase fault, different examples of faults between phase \( A \) and phase \( B \) are simulated by varying the number of shorted turns \( N_A \) and \( N_B \) and using a resistance \( R_d \) to limit the fault current to \( I_{d} = 4.24 \text{ A}. \) Tables 5 and 6 represent the magnitude of \( I_2, \) and the phase angle \( \phi_2 \) of the negative sequence current respectively. Referring to Table 5, the magnitude of \( I_2 \) shows the importance of the fault since the magnitude of \( I_2 \) increases with the increase in the fault. But, the magnitude of \( I_2 \) seems to be insignificant in giving to information about the phase most affected by the fault. This can be explained by the fact that the value of \( I_2 \) remains the same if the number of shorted turns in the two phases is commuted symmetrically, e.g. for fault of \((N_A = 15\) and \(N_B = 80)\) and another symmetrical fault of \((N_A = 80\) and \(N_B = 15)\), \( I_2 \) has the same value 0.27 A in the two cases of fault.
Table 5
Simulated magnitude of \( \hat{I}_2 \) (A) under short circuit fault between phase A and phase B \( \hat{i}_d = 4.24 \) A.

<table>
<thead>
<tr>
<th>( N_B )</th>
<th>( \hat{N}_A )</th>
<th>7</th>
<th>15</th>
<th>80</th>
<th>120</th>
<th>330</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 (1.5%)</td>
<td>0.037</td>
<td>0.059</td>
<td>0.255</td>
<td>0.377</td>
<td>1.017</td>
<td></td>
</tr>
<tr>
<td>15 (3.2%)</td>
<td>0.059</td>
<td>0.079</td>
<td>0.27</td>
<td>0.39</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>80 (17.2%)</td>
<td>0.255</td>
<td>0.27</td>
<td>0.422</td>
<td>0.531</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>120 (25.8%)</td>
<td>0.377</td>
<td>0.39</td>
<td>0.531</td>
<td>0.633</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>330 (71.1%)</td>
<td>1.017</td>
<td>1.03</td>
<td>1.15</td>
<td>1.23</td>
<td>1.74</td>
<td></td>
</tr>
</tbody>
</table>

Table 6
Simulated values of \( \phi_2 \) (°) under short circuit fault between phase A and phase B \( \hat{i}_d = 4.24 \) A.

<table>
<thead>
<tr>
<th>( N_B )</th>
<th>( \hat{N}_A )</th>
<th>7</th>
<th>15</th>
<th>80</th>
<th>120</th>
<th>330</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 (1.5%)</td>
<td>60.01</td>
<td>36.29</td>
<td>8.24</td>
<td>5.51</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td>15 (3.2%)</td>
<td>83.72</td>
<td>60.01</td>
<td>16.84</td>
<td>11.55</td>
<td>4.09</td>
<td></td>
</tr>
<tr>
<td>80 (17.2%)</td>
<td>111.6</td>
<td>103.1</td>
<td>60.01</td>
<td>46.8</td>
<td>21.04</td>
<td></td>
</tr>
<tr>
<td>120 (25.8%)</td>
<td>114.3</td>
<td>108.3</td>
<td>73.2</td>
<td>60.01</td>
<td>29.73</td>
<td></td>
</tr>
<tr>
<td>330 (71.1%)</td>
<td>117.6</td>
<td>115.3</td>
<td>98.6</td>
<td>90.05</td>
<td>60.01</td>
<td></td>
</tr>
</tbody>
</table>

On the other hand, from Table 6, it can be seen that the value of \( \phi_2 \) can determine the phase most affected by the fault. First note that all the values of \( \phi_2 \) are ranged between 0° and 120°, which means that the fault is between A and B since these two angles represent, in an opposite rotation sense (because \( I_2 \) is in the inverse sense) the angles of the two phases affected by the fault (A and B in this case). Second, the value of \( \phi_2 \) is usually quite close to the angle of the phase where the fault is more important. Third, for an equal fault in two phases, the value of \( \phi_2 \) is situated in the middle of the angle separating the two phases affected by the fault (60° in this case). Accordingly, the values of \( I_2 \) and \( \phi_2 \) are considered efficient indicators for the detection and the location of phase to phase faults.

Moreover, the simulation of the two other cases of short circuit fault between (A and C) and between (B and C) is also performed and gives the same expected behavior as in the case of fault between (A and B). That is mean that the obtained values of \( \phi_2 \) are ranged between 0° and −120° for faults between (A and C) and ranged between 120° and 240° for faults between (B and C).

4.2. Study of the impact of the ITSC fault

Table 7 represents different examples of ITSC faults in phase A, B, and C, performed with a fault current limited to 4.24A (3 A rms value). It is clear that the magnitude of \( I_2 \) shows the importance of the fault since \( I_2 \) increases with the increase in the fault, but on the other hand it cannot give information about the phase where the fault is occurred. This is because the magnitude of \( I_2 \) maintains the same value in case of a fault in phase A, B, or C. The value of \( \phi_2 \) reveals

Table 7
Different simulated values of \( \hat{I}_2 \) under different ITSC fault in phase A, B and C \( \hat{i}_d = 4.24 \) A.

<table>
<thead>
<tr>
<th>( N_A = N_B = N_C )</th>
<th>( \hat{I}_2 ) (A)</th>
<th>8 (1.5%)</th>
<th>15 (3.2%)</th>
<th>80 (17.2%)</th>
<th>120 (25.8%)</th>
<th>330 (71.1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_2 ) (°)</td>
<td>-0.0005</td>
<td>-0.008</td>
<td>-0.08</td>
<td>-0.125</td>
<td>-0.358</td>
<td></td>
</tr>
<tr>
<td>( \phi_2 ) (°)</td>
<td>120</td>
<td>120</td>
<td>119.9</td>
<td>119.9</td>
<td>119.6</td>
<td></td>
</tr>
<tr>
<td>( \phi_2 ) (°)</td>
<td>-120</td>
<td>-120</td>
<td>-120.1</td>
<td>-120.1</td>
<td>-120.4</td>
<td></td>
</tr>
</tbody>
</table>
the localization of the faulty phase. Note that the angle phase of the phase $B$ and $C$ are here in an inverse rotating sense as compared to the direct sense of the power supply. Therefore the value of $I_2$ and $\varphi_2$ are considered as efficient indicators of the ITSC fault.

For further investigation of the behavior of $I_2$, Fig. 11 represents the behavior as a function of the number of the shorted turns for different values of fault current $i_d$ flowing through the resistance. However, the magnitude of $I_2$ is proportional to the number of the shorted turns as well as to the fault current $i_d$.

4.3. Study of the impact of single phase to ground fault

To investigate single phase to ground fault, different values of $I_2$ and $I_0$ are simulated and represented in Table 8. These examples of fault correspond to different short circuits between specific number of turns in each phase and the neutral of the source. In simulation, the fault current is limited to $i_d = 1.5 \text{ A} (1.1 \text{ A rms value}).$ Note that the behavior of phase to ground fault has the same behavior of an ITSC fault except that it is characterized by the existence of a significant zero sequence current $I_0$. It is important to note that the value of $I_0$ is always equal to one-third of the fault current $i_d (I_0 = 1/3 \cdot i_d)$. However, the value of $I_0$ a useful and reliable indicator to discriminate between ITSC faults and phase to ground faults.

5. Interpretation of the results

Through the above study of the simulated behavior of the symmetrical components under ITSC, phase to phase and single phase to ground faults, it can be noted that for each stator fault, the phase angle of the negative sequence

<table>
<thead>
<tr>
<th>$N_A = N_B = N_C$</th>
<th>7 (1.5%)</th>
<th>15 (3.2%)</th>
<th>80 (17.2%)</th>
<th>120 (25.8%)</th>
<th>330 (71.1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_2$ (A)</td>
<td>0.007</td>
<td>0.016</td>
<td>0.0862</td>
<td>0.131</td>
<td>0.361</td>
</tr>
<tr>
<td>$I_0$ (A)</td>
<td>0.511</td>
<td>0.499</td>
<td>0.498</td>
<td>0.506</td>
<td>0.507</td>
</tr>
<tr>
<td><strong>For phase A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varphi_2$ (°)</td>
<td>-9.954</td>
<td>-4.504</td>
<td>-0.751</td>
<td>-0.459</td>
<td>-0.043</td>
</tr>
<tr>
<td>$\varphi_0$ (°)</td>
<td>-11.39</td>
<td>-5.002</td>
<td>-0.703</td>
<td>-0.390</td>
<td>-0.023</td>
</tr>
<tr>
<td><strong>For phase B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varphi_2$ (°)</td>
<td>110.8</td>
<td>116</td>
<td>119.3</td>
<td>119.6</td>
<td>120</td>
</tr>
<tr>
<td>$\varphi_0$ (°)</td>
<td>-130.39</td>
<td>-124.5</td>
<td>-120.5</td>
<td>-120.3</td>
<td>-120</td>
</tr>
<tr>
<td><strong>For phase C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varphi_2$ (°)</td>
<td>-130</td>
<td>-124.5</td>
<td>-120.8</td>
<td>-120.5</td>
<td>-120</td>
</tr>
<tr>
<td>$\varphi_0$ (°)</td>
<td>108.6</td>
<td>115</td>
<td>119.3</td>
<td>119.6</td>
<td>120</td>
</tr>
</tbody>
</table>
current allows the location of the fault. In fact, a phase angle of $120^\circ$ corresponds to a fault in phase $B$, a phase angle of $-120^\circ$ corresponds to a fault in phase $C$, while for a fault in phase $A$ taken as the origin of phases, the phase angle of the negative sequence current is $0^\circ$. For both the ITSC fault and the phase to ground fault, the negative sequence current has the same behavior, it is only by the zero-sequence current that the two kinds of fault can be discriminated. For phase to phase fault, the phase angle of the negative sequence current is situated between the two angles of the two phases affected by the fault. This angle depends essentially on the number of shorted turns involved in each phase.

The amplitude of the fault current is directly related to the magnitude of the fault in terms of amplitude of the fault current in combination with the number of shorted turns. Only the product of these two parameters can be estimated. Knowledge of the windings temperature can separate these two parameters, because the additional losses are proportional to the number of turns in fault but depend on the square of the fault current.

6. Conclusion

An original simplified model dedicated to fault diagnosis is presented in this paper. It is developed with the aim of simulating, in an easy way, different stator faults as inter-turns short circuit, phase to phase and single phase to ground faults. This developed model is based on the use of multiple-coupled circuits where the magnetic interaction is considered only between the stator windings, while the rotor is considered independent of the stator and under the same forced common flux. The effectiveness of the simplified model was verified by simulation referring to the classic multiple-coupled circuit model, and validated experimentally using a 1.1 kW motor having the same characteristics as those of the simulated machine. By neglecting the measurement errors, the simulated values show a good agreement with the experimental results.

In addition, the behavior of the simplified model of a large motor of 110 kW is also tested. Its successful performance has been presented through a comparison between the SM and the CM for this large motor under the same fault conditions. This confirms that the proposed simplified model is suitable to simulate the steady-state behavior of any motor ranging from small to large induction motors.

Furthermore, a study of the impact of the different stator faults on the symmetrical components of the current is introduced in order to extract reliable and powerful indicators of faults which are the negative and the zero sequence current. Therefore, it can be inferred that the proposed simplified model is a reliable and suitable model to simulate the steady-state behavior of the induction motor under different stator faults conditions with a good level of accuracy.

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