PARK MODEL OF SQUIRREL CAGE INDUCTION MACHINE INCLUDING SPACE HARMONICS EFFECTS

Mohamed Boucherma — Mohamed Yazid Kaikaa — Abdelmalek Khezzar

An accurate and simpler approach for modelling and simulating the dynamic behavior of squirrel cage induction machines is presented here. The model is based on multiple coupled circuits and takes into account the geometry and winding layout of the machine. All inductances are derived by means of the winding function approach (WFA) and are integrated with the decomposition into their Fourier series. An important issue in such effort is the modelling of the induction motor including rotor slot harmonics (RSH) under symmetrical and asymmetrical conditions, with minimum computational complexity. Simulations results have shown excellent match with theoretically predicted RSH components.

Keywords: induction machine, Park model, space harmonics, winding function, diagnostics

1 INTRODUCTION

For past 30 years, the dynamic behaviour of induction machine has received a considerable attention in most researched works. However, the majority of models are based on the simple idealist machine without tacking into account the physical layout of the stator and rotor windings. For example, the conventional Park (dq) model and the development of its current, torque and power relationships are based on the assumptions that the rotating mmf produced by stator winding excitation is sinusoidally distributed in space and that the rotor mmf due to the slip frequency induced currents is similarly distributed. It is apparent that these models are not suitable for diagnosis and/or sensorless speed estimation by investigating the rotor slot harmonics (RSH). Therefore, there is a real need to derive an accurate model which can take into account the effect of the field harmonics both in time and in space.

There are several papers devoted to this problem; in the papers [1, 2], the space harmonics are taking into account by means of the winding function approach (WFA). The model developed is based directly on the geometry of the induction machine and the physical layout of all windings. This model has been next extended to monitor some mechanical and electrical defaults: inter-turn short windings. This model has been next extended to monitor some mechanical and electrical defaults: inter-turn short windings [3,4], rotor eccentricity [5,6] and to estimate the rotor speed for the control purpose [7,8,9].

In this paper, an alternative way for formulating the suitable model is suggested, using the decomposition into Fourier series of the mutual inductance matrix and the presentation of the induction motor in Park frame. It is found that an accurate motor simulation can be achieved with the proposed method, in addition, this speeds up significantly the computer simulation time, and makes the process monitoring more reliable. The new model can be extended to the solution of a wide variety of fault and predict the squirrel induction motor response in transient as well as in steady-state modes of operation. The detailed depiction of the procedure needed to implement such an accurate model with simulation results is the subject of this paper.

2 THEORETICAL BACKGROUND: ROTOR SLOT HARMONICS

The air gap field of an induction motor fed by a sinusoidal voltage supply waveform comprises a wide range of different space harmonics. The following analysis assumes that these air-gap flux harmonics are a result of the interaction of air-gap permeance and harmonic magnetomotive force (MMF) waves. Only harmonics due to slotting are considered here (rotor slot harmonics).

It has been shown that the rotor slot harmonics (RSH) are generated in the stator line current for healthy machine at frequencies given by [3,5]:

\[ f_{sh} = \left( \frac{\lambda N_r}{p} (1 - s) \pm 1 \right) f \]  

(1)

Note that only RSH who's their order belongs to the following set can be detected [9,10]:

\[ G = \left\{ (6k \pm 1)_{k=1,2,3} \cup \left( \frac{\lambda N_r}{p} \pm 1 \right)_{\lambda=1,2,3,\ldots} \right\} \]  

(2)

For a rotor with asymmetry (broken bar, end-ring fault or eccentricity) Thomson and al. have shown that the rotor slot harmonic frequencies are [11]:

\[ f_{hk} = \left( \frac{\lambda N_r}{p} (1 - s) \pm 1 \pm 2ks \right) f_s \]  

(3)

where: \( p \) — is the number of pole pairs and \( S \) is the slip.; \( f_s \) — is the fundamental supply frequency; \( N_r \) — is the number of rotor slot (bars0; \( \lambda \) — is a positive integer.

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3 ELECTRICAL EQUATIONS

Consider a squirrel cage induction machine having three identical and symmetrical phases in the stator. The rotor cage having \((N_r = n)\) bars is viewed as \(n\) identical spaced loops and the currents distribution can be specified in terms of \(n + 1\) independent rotor currents. These currents are formed of \(n\) rotor loop currents \([i_{nr}]\) plus a circulating current in one of the end rings \(i_e\) (Figure 1).

The mesh model is based on a coupled magnetic circuits approach and by making the following assumptions:

- The state of operation remains far from magnetic saturation.
- The magnetic permeability of iron is considered to be infinite and the air-gap is very small and smooth.

The stator voltage equations in vector matrix form can be written as:

\[
[V_3a] = [R_s][i_3a] + \frac{d}{dt}[\psi_3a],
\]

\[
[R_3] = [0] = \begin{bmatrix}
R_e/n & \cdots & i_e & \frac{d}{dt}[\psi_e] \\
R_e/n & \cdots & R_e & \cdots & i_e & \frac{d}{dt}[\psi_e] \\
\vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\psi_3a = [L_s][i_{3a}] + [M_{sr}][i_{nr}] \\
[\psi_{sr}] = [M_{sr}][i_{3a}] + [M_{sr}][i_{nr}] \\
[L_s] & L_e/n & \cdots & \vdots & \vdots & \cdots & \psi_e \\
L_e/n & \cdots & L_e & \cdots & \vdots & \cdots & \cdots
\end{bmatrix}
\]

As usual, \([V]\) is the voltage matrix, \([i]\) is the current matrix. \([R_s]\) and \([R_r]\) are the stator and rotor resistance matrices respectively; \([\Psi_s]\) and \([\Psi_r]\) are the stator and rotor flux linkage matrices respectively. and are the stator and rotor matrices of inductances respectively. \([M_{sr}]\) is the mutual matrix inductances between the stator and rotor. \([M_{sr}]\) is the transpose of \([M_{sr}]\).

\[
[i_{nr}] = [i_{r1} \ i_{r2} \ \cdots \ i_{rn}]^T
\]

\[
[V_{3a}] = [V_{s1} \ V_{s2} \ V_{s3}]^T
\]

\[
[i_{3a}] = [i_{s1} \ i_{s2} \ i_{s3}]^T
\]

\[
[R_s] = R_s \cdot 1_{3x3}
\]

The matrix \([R_s]\) is \(n\) by \(n\) symmetric where, \(R_{b,k-1}\) is resistance of the bar number \(k\) and \(R_e\) is the end ring segment resistance.

\[
[R_s] = \begin{bmatrix}
R_{b0} + R_{b(N_r-1)} + \frac{2R_e}{N_r} & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & 0 \\
-R_{b(k-1)} & \cdots & \cdots & \cdots \\
\vdots & \cdots & \cdots & \cdots & \cdots \\
R_{bk} + R_{b(N_r-1)} + \frac{2R_e}{N_r} & \cdots & 0 \\
0 & \cdots & \cdots & \cdots \\
0 & \cdots & \cdots & \cdots
\end{bmatrix}
\]

4 CALCULATIONS OF INDUCTANCES

The inductances of the above system of equations were calculated using the winding function method, from which inductance between any two windings "\(i\)" and "\(j\)" in any electric machine can be computed by the following equation [1, 3, 4]:

\[
L_{ij}(\varphi) = \mu_o L r \int_0^{2\pi} n_i(\varphi, \theta) N_j(\varphi, \theta) d\theta
\]

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, \(e\) is the air gap function, \(L\) is the length of stack and \(r\) is the average radius of air gap. Further on, \(n_i(\varphi, \theta)\) is the winding distribution of coil \(i\); it was introduced to describe the considered coil, and \(N_i(\varphi, \theta)\) is the winding function of coil \(j\); it represents the mmf of the air-gap produced by unit current flowing in the considered coil.
The motor used for simulation in this paper is a three phase, 50 Hz, 2 poles, 36 stator slots and 28 rotor bars. The mutual inductances between stator and rotor are considered to be time-varying, the others inductances are pre-calculated and treated as constant because of the round stator and rotor structure.

\[
\begin{align*}
L_{rr} + 2L_b + \frac{2L_0}{N_r} & \quad M_{rr} \\
\vdots & \quad \vdots \\
M_{rr} - L_b & \quad M_{rr} \\
\vdots & \quad \vdots \\
M_{rr} & \quad M_{rr} \\
L_{rr} + 2L_b & \quad M_{rr} - L_b \\
\vdots & \quad \vdots \\
M_{rr} & \quad M_{rr} \\
\end{align*}
\]  

\[
[L_e] =
\begin{bmatrix}
L_{rr} + 2L_b + \frac{2L_0}{N_r} & \cdots & M_{rr} \\
\vdots & \ddots & \vdots \\
M_{rr} & \cdots & M_{rr} - L_b \\
\vdots & \ddots & \vdots \\
M_{rr} - L_b & \cdots & \cdots \\
L_{rr} + 2L_b & \cdots & \cdots \\
\vdots & \ddots & \vdots \\
M_{rr} & \cdots & M_{rr}
\end{bmatrix}
\quad (14)
\]

The space distribution of the mutual inductance is not sinusoidal. This implies that the mutual inductances matrix presents harmonics with respect to the electrical angle \( \theta \). Consequently, this matrix can be resolved into its Fourier series [12]:

\[
[M_{sr}] = \sum_{h=1}^{\infty} M_{srh} \begin{bmatrix}
\cdots & \cos(h(\theta + \varphi_h + ka)) & \cdots \\
\vdots & \ddots & \vdots \\
\cos(h(\theta + \varphi_h + ka) - \frac{2h\pi}{a}) & \cdots \\
\cos(h(\theta + \varphi_h + ka) + \frac{2h\pi}{a}) & \cdots \\
\end{bmatrix}
\quad (15)
\]

where \( \xi_h \) is the initial phase angle, and \( k = 0, 1, 2, \ldots, N_r \) and

\[
\xi_h = \begin{cases} +1 & \text{if } h \in F \\ -1 & \text{if } h \in B \end{cases}
\]

and \( F = \{1, 7, 13, 19, \ldots \} \), set of forward harmonic components, and \( B = \{5, 11, 17, \ldots \} \) set of backward harmonic components.

**Table 1.** Mutual inductance between the stator phase a and the first rotor loop

<table>
<thead>
<tr>
<th>Inductance ( M_{sar1} ) (H)</th>
<th>Angle ( \theta ) (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_{sar1}N_a (\frac{-2}{3}a) )</td>
<td>( 0 \leq \theta &lt; \frac{\pi}{9} - a )</td>
</tr>
<tr>
<td>( \mu_{sar1}N_a \frac{2}{3}(\theta - \frac{\pi}{9}) )</td>
<td>( \frac{\pi}{9} - a \leq \theta &lt; \frac{\pi}{9} )</td>
</tr>
<tr>
<td>0</td>
<td>( \frac{\pi}{9} \leq \theta &lt; \frac{4\pi}{9} - a )</td>
</tr>
<tr>
<td>( \mu_{sar1}N_a \frac{2}{3}(\theta + a - \frac{2\pi}{9}) )</td>
<td>( \frac{4\pi}{9} - a \leq \theta &lt; \frac{2\pi}{9} - a )</td>
</tr>
<tr>
<td>( \mu_{sar1}N_a \frac{2}{3}a )</td>
<td>( \frac{2\pi}{9} \leq \theta &lt; \frac{\pi}{3} - a )</td>
</tr>
<tr>
<td>( \mu_{sar1}N_a (\frac{\theta}{3} + a - \frac{\pi}{9}) )</td>
<td>( \frac{\pi}{3} - a \leq \theta &lt; \frac{\pi}{3} )</td>
</tr>
<tr>
<td>( \mu_{sar1}N_a \frac{a}{3} )</td>
<td>( \frac{\pi}{3} \leq \theta &lt; \pi - a )</td>
</tr>
<tr>
<td>( \mu_{sar1}N_a \frac{2}{3}(\theta + \frac{2}{3}a + \frac{\pi}{9}) )</td>
<td>( \pi - a \leq \theta &lt; \pi )</td>
</tr>
</tbody>
</table>

**Fig. 2.** Winding distribution of stator phase a (top), Winding function of rotor loop 1 (bottom)

**Fig. 3.** Mutual inductance \( M_{sar1}, M_{sbr1}, M_{scr1} \)

**Fig. 4.** Mutual inductance \( M_{sar1}, M_{sar2}, M_{sar3}, M_{sar4} \)
5 PARK TRANSFORMATION

The Park transformation is a well-known three-phase to two-phase transformation in machine analysis. The transformation equation is of the form:

$$[X_{sodq}] = [X_{so} \ X_{sd} \ X_{sq}]^T = [P_3(\theta_s)]^T [X_{3s}]$$ \quad (16)

where the adq transformation matrix is defined as

$$[P_3(\theta_s)] = \begin{bmatrix} \frac{1}{\sqrt{2}} \cos(\theta_s) & -\sin(\theta_s) \\ \frac{1}{\sqrt{2}} \cos(\theta_s - 2\pi/3) - \sin(\theta_s - 2\pi/3) \\ \frac{1}{\sqrt{2}} \cos(\theta_s + 2\pi/3) - \sin(\theta_s + 2\pi/3) \end{bmatrix}$$ \quad (17)

Here $\theta_s$ is the angular displacement between the Park reference frame and the first phase of the stator.

Transforming the above sets of stator abc variables to the Park reference frame using (11), we obtain

$$[V_{sodq}] = [R_s][i_{sodq}] + \frac{d}{dt}([\psi_{sodq}]) + \frac{d\theta}{dt} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} [\psi_{sodq}]$$ \quad (18)

$$\begin{bmatrix} [V_c] \\ V_c \end{bmatrix} = \begin{bmatrix} [R_e] & R_e/n \\ R_e/n & \cdots \\ \cdots & R_e \end{bmatrix} \begin{bmatrix} [i_{rn}] \\ i_{c} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_{rn} \\ \psi_{c} \end{bmatrix}$$ \quad (19)

where

$$[\psi_{sodq}] = [L_{sc}][i_{sodq}] + [M_{srd}][i_{nr}]$$ \quad (20)

$$[\psi_{nr}] = [M_{srd}]^T[i_{sodq}] + [L_r][i_{rn}] + \frac{L_e}{n} \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} [i_{c}]$$ \quad (21)

where

$$[L_{sc}] = [P_3(\theta_s)]^{-1} [L_s] \cdot [P_3(\theta_s)]$$ \quad (22)

$$[M_{srd}] = [P_3(\theta_s)]^{-1} [M_{sr}] = \sqrt{\frac{3}{2}} \sum_{h=1}^{\infty} M_{sh} h - \xi_h$$

$$\times \begin{bmatrix} \cdots & \cdots & 0 \\ \cdots & \cdots & -\sin((h - \xi_h)\theta + h\varphi_h + h\alpha) \\ \cdots & \cdots & \xi_h \cos((h - \xi_h)\theta + h\varphi_h + h\alpha) \end{bmatrix}$$ \quad (27)

For the purpose of digital simulation, equations (18) and (19) are presented in state variable form with currents as state variables

$$[L] \frac{d}{dt} [I] = [V] - [R][I]$$ \quad (28)

where

$$[I] = \begin{bmatrix} [i_{sodq}] \\ [i_{rn}]_{n \times 1} \\ i_{c} \end{bmatrix}, \quad [V] = \begin{bmatrix} [\psi_{sodq}] \\ [V_{rn}] = [0]_{n \times 1} \\ V_c = 0 \end{bmatrix}$$ \quad (29)

$$[L] = \begin{bmatrix} [L_{sc}] & [M_{srd}]^T \\ [L_r] & \frac{L_e}{n} \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} \end{bmatrix}$$ \quad (30)

$$[R] = \begin{bmatrix} [R_s] + \frac{d}{dt} [J_{22}] [L_{sc}] \frac{d}{d\theta} [M_{srd}] + \frac{d}{dt} [J_{22}] [M_{srd}] \\ \frac{d}{d\theta} [M_{srd}]^T \\ [0]_{1 \times 3} \\ \frac{L_e}{n} \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} \end{bmatrix} [R_r]$$ \quad (31)

From (20) and (21) we obtain:

$$\frac{d}{dt} [\psi_{sodq}] = [L_{sc}][i_{sodq}] + \frac{d}{dt} [\psi_{sodq}]$$
6 MECHANICAL EQUATIONS

The mechanical equations can be expressed as
\[
\frac{d\omega}{dt} = \frac{p}{J}(\Gamma_e - \Gamma_r), \quad (32)
\]
\[
\frac{d\theta}{dt} = \omega \quad (33)
\]
where \(\Gamma_e\) is the electromagnetic torque produced by the motor, \(\Gamma_r\) is the load torque and \(\omega\) is the rotor speed.

Using the basic principle of energy conversion, the torque developed by the machine \(\Gamma_e\) can be obtained by considering the change in co-energy “\(W_{co}\)” of the system produced by a small change in rotor position when the currents are held constant.

\[
\Gamma_e = \left[ \frac{\partial W_{co}}{\partial \theta_{mec}} \right]_{(i_{3s}, j_{rn}\text{ const.})} \quad (34)
\]
as the magnetic nonlinearity is ignored, the co-energy is given by
\[
W_{co} = \frac{1}{2} \left[ [i_{3s}]^T [i_{rn}]^T \right] \left[ \begin{bmatrix} L_s & [M_{sr}] & \ldots \end{bmatrix} \right] \left[ \begin{bmatrix} i_{3s} \end{bmatrix} \right], \quad (35)
\]
\[
\Gamma_e = [i_{3s}]^T \frac{\partial}{\partial \theta_{mec}} [M_{sr}] [i_{rn}], \quad (36)
\]
\[
\Gamma_e = p[i_{sdq}]^T [p_3(\theta_s)]^T \frac{\partial}{\partial \theta} [M_{sr}] [i_{rn}], \quad (37)
\]
Substituting (15) and (17) in (37) leads to:
\[
\Gamma_e = \\
\sqrt{3} \frac{p}{2} \sum_{h=1}^{\infty} \left\{ i_{qs} \sum_{k=0}^{N_e-1} I_{rk} \xi_k \cos \left( h(\theta + \phi_h + ka) - \xi_k \theta_s \right) \\
- i_{ds} \sum_{k=0}^{N_e-1} I_{rk} \sin \left( h(\theta + \phi_h + ka) - \xi_k \theta_s \right) \right\} \quad (37)
\]

7 SIMULATION RESULTS

7.1 Analysis of Healthy machine

The differential equations derived above can be solved by fourth-order Runge-Kutta method. The simulation study was conducted using a machine of 3 hp, 3 phases, 50 Hz, 36 stator slots, 28 rotor bars and 2 poles machine.

For purposes of comparison the healthy machine was first modelled using the conventional Park d-q model. (Figure 5) The same machine was simulated next using the proposed model. The simulation results are carried out at a slip around 0.035 (Figure 6)

Comparison of the two simulation traces shows very good correlation. The effects of rotor slot harmonics can be observed to have a more significant affect on the electromagnetic torque.

Fig. 5. Acceleration transient using conventional dq mesh model under sinusoidal voltage excitation.

Fig. 6. Acceleration transient using the proposed model under sinusoidal voltage excitation.

Fig. 7. Normalized FFT of the stator current in quasi steady-state. Conventional dq mesh model (blue line), proposed one (red line).

Fig. 8. Simulated, normalized FFT spectrum of machine line current of healthy induction motor with balanced supply (top) and with 5% unbalanced supply, (bottom)
Figure 7 shows the FFT normalized to the fundamental of the line current for the conventional and the proposed d-q model. It can be easily seen the presence of the rotor slot harmonics in the case of the proposed model.

Also, we can verify the total agreement between theoretical formulas (1) and (2) and the simulations results.

For bars and as predicted theoretically, only one RSH can be seen. The second RSH did not show up because of the pole pair number associated \( \left( \frac{N_r}{p} - 1 = 27 \right) \) do not belong to \( G \) (equation 2).

In order to verify that the second RSH is due to the reverse rotating field \([11]\), five percent of unbalance was added to one of the supply phase voltages. The result is shown in Figure 8. It is clear that RSH2 can now be seen.

### 7.2 Analysis of machine with broken rotor bars

The studied machine was simulated with incipient broken bars under similar load and inertia conditions. To simulate a broken rotor bar, we increase its resistance by a coefficient such as the current in the bar is closest to zero. The results are shown in Figure 9. In this case, broken bar related harmonic components are clearly located around the fundamental (Figures 10).

These classical twice slip frequency sidebands are not the only effect due to rotor broken bars. There are other frequencies induced around all rotor slot harmonics (Figure11).

![Fig. 9. Simulated, normalized line current spectra of machine with 4 broken bars](image)

![Fig. 10. Zoomed spectrum of the stator current around the fundamental](image)

These harmonic components come from the mathematical relations given in (3), they can give additional information about the rotor asymmetry and its gravity.

### 8 CONCLUSION

An accurate transient model of squirrel cage induction machine has been presented. This model is based on multiple coupled circuits and takes into account the geometry and winding layout of the machine, without complexity in equations formulation or long computation.

Model equations are directly extracted by the decomposition into Fourier series of the mutual inductance matrix and the presentation of the induction motor in dq frame. This model is helpful in quantifying the rotor slot harmonics under healthy as well as faulty condition. It has been shown that:

- The reverse rotating field caused by the supply unbalance induce some of space harmonics in the stator current.

- For machines with broken rotor bars, the stator current spectrum contains other significant harmonic components than \((1 \pm 2k)s f_s\). These harmonics can be located around all RSH.

### 9 APPENDIX

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>220 V</td>
</tr>
<tr>
<td>( p )</td>
<td>1</td>
</tr>
<tr>
<td>( f_s )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>( N_r )</td>
<td>28</td>
</tr>
<tr>
<td>( e )</td>
<td>0.003 m</td>
</tr>
<tr>
<td>( J )</td>
<td>( 4.5 \times 10^{-3} ) kg m²</td>
</tr>
<tr>
<td>( L_b )</td>
<td>0.1 mH</td>
</tr>
<tr>
<td>( R_s )</td>
<td>9.2Ω</td>
</tr>
<tr>
<td>( R_b )</td>
<td>( 68 \times 10^{-6} )Ω</td>
</tr>
<tr>
<td>( R_e )</td>
<td>( 1.3 \times 10^{-6} )Ω</td>
</tr>
<tr>
<td>( L_{rp} )</td>
<td>( 0.17 \times 10^{-6} ) H</td>
</tr>
<tr>
<td>( L_{re} )</td>
<td>( 2 \times 10^{-9} ) H</td>
</tr>
</tbody>
</table>
REFERENCES


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