Monitoring and diagnostic methods for eccentricity faults in the induction motor

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Abstract—This work concerns the monitoring and diagnosis of eccentricity faults in induction motors. The success of the type of electric motors is mainly due to its simplicity of construction, mechanical robustness, and low cost of manufacturing. Therefore, it is frequently used in industrial applications. These engines are subjected during operation to different kinds of constraints (thermal, electrical, magnetic, mechanical and environmental). The accumulation of these constraints leads to defects in different parts of the engine, which results in lost production and costly repairs. The monitoring and diagnosis of faults have become major necessities to detect failure of electric motors. In this paper, we develop an approach for the detection and diagnosis of faults eccentricities in induction motors. To this end, we build models for each mode of engine operation (normal operation and faulty behaviors). We detect online the faults with the analysis of residuals obtained from the reference model. We diagnose the faults by the analysis of residuals obtained from faulty models.

Keywords—Monitoring, diagnosis, fault detection, induction motor, residuals.

I. INTRODUCTION (HEADING 1)

The occurrence of faults in induction motor results in repair cost and lost production [1]. To safeguard the interests of the companies and ensure the safety of persons and equipments, it is essential to develop monitoring and diagnosis facilities. Several methods exist [2], [3] and [7]. The choice of the method is linked to the knowledge that you wish to acquire about the system, but also to the expected complexity. In our study, we propose a method based on the analysis of residuals from reference (i.e. fault free) and faulty models. This method has two steps:

1- Online fault detection ;
2- Offline fault diagnosis.

The principle of this method is illustrated by the following schemes:

The figure 1 presents the principle of fault detection by using the error resulting from the comparison of the model output with the actual measurements on engine. The second step is the diagnosis of the faults based on the comparison of the measurements recorded at the first step with the expected values estimated with the faulty models.
II. REFERENCE MODEL DESIGN

The reference model is based on an approximation of magnetically coupled circuits where the current in each mesh of the rotor cage is an independent variable [2], [9]. In the following equation $X_s$ stand for a variable of stator and $X_r$ for a variable of rotor. The model used in simulation is presented by equation (1):

$$[v_s] = [R_s][I_s] + \frac{d}{dt}[\Psi_s]$$

The equation of the current flow is presented by (2):

$$[\Psi_s] = [L_{sr,r}][I_s] + [L_{sr,t}][I_t]$$

The vectors of voltage and current in the stator and rotor are:

$$[v_s] = [v_{sa}, v_{sb}, v_{sc}]^T$$

$$[v_t] = [0, 0]$$

The dimension of stator current is 1x3 and the rotor current is of dimension 1x(N_b+1). The stator parameters correspond to the matrices $R_s$ and $L_{sr}$ of dimension 3x3:

$$[R_s] = \begin{bmatrix} R_{sa} & 0 & 0 \\ 0 & R_{sb} & 0 \\ 0 & 0 & R_{sc} \end{bmatrix}$$

$$[L_{sr}] = \begin{bmatrix} L_{saa} & L_{sab} & L_{sac} \\ L_{sba} & L_{sbb} & L_{sbc} \\ L_{sca} & L_{scb} & L_{ssc} \end{bmatrix}$$

with $L_{sii} = L_{sa} + L_{sb}$. $L_{sii}$ is the inductance of the $i^{th}$ phase and $L_{sij}$ is the stator mutual inductance between the $i^{th}$ and $j^{th}$ phase ($i \neq j$). The inductance between the stator phases and the rotor meshes is presented by the matrix $L_{sr}$ of dimension 3x(N_b+1):

$$[L_{sr}] = \begin{bmatrix} L_{sar1} & L_{sar2} & \ldots & L_{sarN_b} & L_{sare} \\ L_{sbr1} & L_{sbr2} & \ldots & L_{sbrN_b} & L_{sbrre} \\ L_{scr1} & L_{scr2} & \ldots & L_{scrN_b} & L_{scree} \end{bmatrix}$$

with $L_{sij}$ the mutual inductance between the stator phase $i$ ($i=a, b$ and $c$) and ring shorted.

The matrices of the rotor resistances and inductances are of dimension ($[N_b+1]x(N_b+1)$), they are represented by equations (8) and (9):

$$[R_r] = \begin{bmatrix} 2(R_e + R_{r1}) & -R_e & 0 & \ldots & -R_e & -R_e \\ -R_e & 2(R_e + R_{r1}) & -R_e & \ldots & 0 & -R_e \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ -R_e & \ldots & \ldots & 2(R_e + R_{r1}) & -R_e & -R_e \\ -R_e & \ldots & \ldots & -R_e & 2(R_e + R_{r1}) & -R_e \\ -R_e & \ldots & \ldots & \ldots & -R_e & -N_bR_e \end{bmatrix}$$

$$[L_{rr}] = \begin{bmatrix} L_{r1} + 2L_{r2} & L_{r2} & \ldots & L_{rN_b} & L_{rN_b} & L_{rN_b} & \ldots \\ (L_{r1} - L_{r2}) & L_{r2} + 2L_{r3} & \ldots & L_{rN_b} & L_{rN_b} & L_{rN_b} & \ldots \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ (L_{r1} - L_{r2}) & \ldots & \ldots & (L_{r1} + 2L_{r2} + L_{r3}) & L_{rN_b} & L_{rN_b} & \ldots \\ -L_{r1} & \ldots & \ldots & -L_{r1} & -L_{r1} & \ldots & -N_bL_{r1} \end{bmatrix}$$

with:

$L_{0}$: the leakage inductance of a rotor bar,
$L_{e}$: the leakage inductance of a portion of a ring short-circuits,
$L_{ij}$: the mutual inductance of the $i^{th}$ and $j^{th}$ rotor meshes with $i \neq j$.

III. FAULT ECCENTRICITIES

The eccentricity of the motor is defined as an asymmetry in the air gap between the stator and rotor. The eccentricity is divided into two categories: static eccentricity and dynamic eccentricity. The static eccentricity is characterized by the fact the center of the rotor is not equal to the stator center [4] [10]. The dynamic eccentricity is characterized by the fact the central engine turns around the center of the stator. The figure 3, solve the principle of both eccentricity.

![Static and dynamic eccentricities](image)

Let $e$ stands for the dimension of the gap. The presence of air gap eccentricity is modeled by equation (10):

$$e(\theta_s, \theta_r) = e_0 + a_1 \cos(\theta_s) + a_2 \cos(\theta_s - \theta_r)$$

with $e_0$ the size of the gap in the absence of fault, $a_1 = es.e_e$ is the parameter of static eccentricity, $a_2 = ed.e_e$ is the amount of dynamic eccentricity, es and ed are respectively the order of
static and dynamic eccentricity, $\theta_s$ is the angular position in a coordinate system related to the stator, $\theta$ is the angular position of rotor relative to stator [6], [8].

1-Case of static eccentricity $a_2=0$, the expression (10) becomes:

$$e(\theta_s) = e_0 + a_1 \cos(\theta_s)$$  \hspace{1cm} (11)

2-Case of dynamic eccentricity $a_1=0$, the expression (10) becomes:

$$e(\theta, \theta_s) = e_0 + a_2 \cos(\theta_s - \theta)$$  \hspace{1cm} (12)

3-Case of mixed eccentricity $a_1 \neq 0$ and $a_2 \neq 0$.

In the presence of eccentricity fault, the gap function changed as the induction:

$$L_s(\theta) = \frac{1}{\mu_0} \int_{-L_s/2}^{L_s/2} \int_{0}^{2\pi} \left[ F_{ii}(\theta, \theta_s, z) + P(\theta, \theta_s, z) \right] d\theta_s dz$$

The mutual inductance between winding $i$ and $j$, is presented by:

$$L_j(\theta) = \frac{1}{\mu_0} \int_{-L_s/2}^{L_s/2} \int_{0}^{2\pi} \left[ F_{ij}(\theta, \theta_s, z) + F_{ji}(\theta, \theta_s, z) + P(\theta, \theta_s, z) \right] d\theta_s dz$$

with,

- $F_{ij}(\theta, \theta_s, z)$ : the MMF of the winding $j$.
- $P(\theta, \theta_s, z)$ : the permeance of the airgap,
- $r_{moy}(\theta, \theta_s, z)$ : the mean radius of the air-gap.

IV. RESULTS AND ANALYSIS

IV.1. OVERVIEW OF SIMULATION

In this article the behavior of the engine is simulated including a Gaussian measurement noise of zero mean value and amplitude 0.01. The figures 4 to 7 show the current phase of the stator induction motor in different operation modes. Figure 4 depicts the phase A for the healthy engine. Figure 5 depicts the same current with a static eccentricity fault simulated after the instant 0.5 second. Figure 6 stands for a dynamic eccentricity fault simulated after 1 second. Finally, figure 7 depict the current for a mixed eccentricity fault simulated after 1.5 seconds.

IV.2. DETECTION OF FAULTS

This stage concerns the on-line detection of faults, based on the analysis of residual $r_1(t)$ obtained by comparison of measurement and estimates resulting from the model healthy.
\[ r(t) = y(t) - y_1(t) \]  \hspace{1cm} (15)

\( y(t) \) is the current measurement at time \( t \) and \( y_1(t) \) is the estimated current using the model healthy at the same time.

The analysis of residuals is obtained by comparing the residual value with a threshold. Such an analysis is efficient to detect the faults and also to estimate with a good accuracy the time of failure. Indeed, before the fault occurred, the residuals are around zero with small variations due to noise measurement. In the case of static or mixed faults the amplitude of residual increases significantly in comparison with the measurement noise. For dynamic faults, the detection and estimation of \( t_d \) can be obtained using a sequential algorithm for changes detection (maximum likelihood or cumulative sum). The estimated times of failure are:

- \( t_d \) (static fault) = 0.56 s.
- \( t_d \) (dynamic fault) = 1.01 s.
- \( t_d \) (mixed fault) = 1.56 s.

IV.3. DIAGNOSIS OF FAULTS

The diagnosis is performed offline, based on the analysis of residuals \( r_2 \), \( r_3 \) and \( r_4 \) from the comparison of measurements and estimates obtained with the three faulty models (static, dynamic and mixed eccentricities).

\[ r_2(t) = y(t) - f(y_1(t), y_2(t), td) \]
\[ r_3(t) = y(t) - f(y_1(t), y_3(t), td) \]
\[ r_4(t) = y(t) - f(y_1(t), y_4(t), td) \]  \hspace{1cm} (16)

\( y_2(t) \) is the estimated current using the faulty model with static eccentricity fault, \( y_3(t) \) is the estimated current using the faulty model with dynamic eccentricity fault and \( y_4(t) \) is the estimated current using the faulty model with the mixed eccentricity fault. The function \( f(.) \) is a switching function such that \( f(t) = y_1(t) \) for \( t < t_d \) and \( f(t) = f_i(t), i=2,...,4 \) for \( t \geq t_d \).

IV.3.1. CASE OF STATIC ECCENTRICITY

Let consider the case of a static eccentricity fault that occurs at time \( t = 0.5 \) s. This fault is detected according to \( r_1(t) \) (figure 9) and the detection time is 0.56 s. The residuals used for
diagnosis are depicted in figures 12 to 14. The residual \( r_2(t) \) is around 0 whereas the residuals \( r_3(t) \) and \( r_4(t) \) increase significantly after \( t = 0.56 \text{ s} \).

![Fig. 12. Residual \( r_2(A) \) in function of time (s) obtained for a static eccentricity fault](image1.png)

![Fig. 13. Residual \( r_3(A) \) in function of time (s) obtained for a static eccentricity fault](image2.png)

![Fig. 14. Residual \( r_4(A) \) in function of time (s) obtained for a static eccentricity fault](image3.png)

**IV.3.2. CASE DYNAMIC OF ECCENTRICITY**

Let consider the case of a dynamic eccentricity fault that occurs at time \( t = 1 \text{ s} \). This fault is detected according to \( r_1(t) \) (figure 11) and the detection time is 1.01 s. The residuals used for diagnosis are depicted in figures 15 to 17.

![Fig. 15. Residual \( r_2(A) \) in function of time (s) obtained for a dynamic eccentricity fault](image4.png)

![Fig. 16. Residual \( r_3(A) \) in function of time (s) obtained for a dynamic eccentricity fault](image5.png)

![Fig. 17. Residual \( r_4(A) \) in function of time (s) obtained for a dynamic eccentricity fault](image6.png)

**IV.3.2. CASE MIXED OF ECCENTRICITY**

Let consider the case of a mixed eccentricity fault that occurs at time \( t = 1.5 \text{ s} \). This fault is detected according to \( r_1(t) \) (figure 11) and the detection time is 1.56 s. The residuals used for diagnosis are depicted in figures 18 to 20.
Fig. 18. Residual $r_2$ (A) in function of time (s) obtained for a mixed eccentricity fault

Fig. 19. Residual $r_3$ (A) in function of time (s) obtained for a mixed eccentricity fault

Fig. 20. Residual $r_4$ (A) in function of time (s) obtained for a mixed eccentricity fault

V. ANALYSIS OF THE RESIDUALS

From the residuals depicted on figures 12 to 20, it is possible to identify the fault. The signature of each type of faults is different and the matrix of signatures can be detailed from the obtained residuals (according to the use of suitable thresholds):

\[
S = \begin{pmatrix}
0 & 1 & 1 \\
1 & 0 & 1 \\
1 & 1 & 0
\end{pmatrix}
\]

VI. CONCLUSION

In this paper, we applied a method for detecting and diagnosing eccentricity faults in the induction motor. The residuals obtained from the healthy model lead to the detection of faults and to the estimations of the times of failure. The residuals obtained from the faulty models lead to the diagnosis of faults types. The results obtained are satisfactory for the online detection and offline diagnosis of faults when the faults are uncorrelated and their magnitude are significantly larger.

VII. MOTOR PARAMETERS

Number of bar rotor: $q = 16$,
Stator resistance: $R_s = 9.2 \Omega$,
Bar resistance: $R_b = 68 \times 10^{-6} \Omega$,
Bar inductance: $L_{cb} = 0.114 \times 10^{-6} H$,
Ring resistance: $R_e = 43.79 \times 10^{-8} \Omega$,
Ring inductance: $L_e = 2 \times 10^{-9} H$,
Number of poles $2p = 2$,
Inertia moment: $J_f = 0.0045$,
Frequency: $f_s = 50 \text{Hz}$,
Rotor diameter: $R_R = 2.557 \times 10^{-3} m$,
Permeability: $\mu_0 = 4 \pi \times 10^{-7}$,
Inductance loss: $L_f = 0.08 H$,
Magnitude of noise: $b = 0.01$;
Numerical increment: $h = 0.001$

REFERENCES


