NON-INVASIVE TORQUE ESTIMATION FOR BROKEN BAR DETECTION IN INDUCTION MOTORS

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Abstract

Rotor asymmetries lead to perturbations of air-gap flux patterns in induction machines. These perturbations in flux components affect a number of components including currents and electromagnetic torque. The supervision of these signals enables early detection of such faults and assists in fault diagnosis. This paper studies the detection of rotor imperfections by spectral analysis of the electromagnetic torque, computed by two stator flux estimators using only non-invasive sensors such as current and voltage sensors. In a first approach, the Extended Luenberger Observer (ELO) is used to estimate stator flux components as well mechanical velocity. A second approach uses a nonlinear High Gain Observer (HGO) for the same purposes. Experimental results and comparison show the significant potential of these methods in detecting these types of faults.

1 Introduction

A broken rotor bar is a major problem for large induction motors. This mechanical fault does not initially cause failure of the induction motors, but there can be serious secondary effects. For example, broken parts of the bar can travel at high velocity, hitting the stator windings. This can cause serious mechanical damage to the insulation, and lead to a winding failure. Such unexpected shutdowns have a cost, in terms of both time and money, which could be avoided by the use of some form of early warning system. In general, on-line condition monitoring and diagnostics require the sensing and analysis of signals that contain specific information characterizing the process of deterioration, the problem, or the fault to be detected. Over the last twenty years various monitoring and diagnostic strategies have been proposed for the diagnosis of problems in induction motors. These strategies are usually based on spectral analysis of electrical signatures such as stator currents or electromagnetic torque. Commercially available diagnostic systems identify characteristic spectral components, in order to aid an expert in evaluating the health of a machine. Rotor asymmetries such as broken rotor bars contribute to the distortion of currents in rotating machines, since these asymmetries give rise to sideband frequencies around the fundamental harmonic in the current spectrum. The main disadvantage of these signatures resides in load-dependent small frequency shifts in the spectrum, especially when the load is weak [1,3,6,9,11]. Other studies, as in [5] have proposed a spectral analysis of the current Park vector modulus, which uses the fact that the spectrum does not contain a fundamental component, but only relative frequencies directly linked to the fault, thus rendering these components easier to isolate. [4,12,13] study the spectral analysis of partial and total instantaneous powers. The spectrum of partial instantaneous powers contains a double fault signature: the first is shown by the appearance of components within the two lateral bands located around twice the fundamental frequency, while the second is shown at low frequencies by the appearance of components at the fault's characteristic frequencies [4].
None of the above-mentioned methods requires knowledge of electrical parameters, which is why these methods are termed external diagnostic methods. Internal diagnostic methods, on the other hand, use electrical parameters and a model of the machine in order to estimate state components such as stator or rotor flux, or electromagnetic torque (EMT). [10], [15] study the spectral analysis of the EMT, computed from stator flux estimation and stator current measurement. This method estimates the stator flux without any correction step, which means that the accuracy of flux estimation is low. Others, like in [7], [8] have proposed analyses of the EMT deduced from the observed rotor flux using linear observers like the Luenberger Observer, and Kalman filtering applied to the reduced model of the machine.
This article presents two new fault detection methods based on spectral analysis of the electromagnetic torque, which is obtained by stator flux estimation. This estimation is provided through two approaches using the Extended Luenberger Observer and the High Gain Observer (HGO) applied to the complete order model. In this paper, section 2 reviews the complete order model of the induction motor, the Luenberger Observer estimation method extended to the mechanical velocity, and an HGO applied to the same complete model. Results and a comparison between the two approaches are presented in section 3.

2 Theoretical development

The electromagnetic torque of an induction motor can be computed from certain known motor variables such as stator currents and rotor flux, or stator currents and stator flux.

Stator flux can be computed simply by using an Open Loop method, which is not very accurate as it uses only a prediction step for the state vector estimation. Alternatively, state vector components can be computed from model-based observers such as Luenberger or High Gain Observers, which take into consideration a predictive step and a correction step. In this paper observers are applied to the complete order model of the induction machine.

2.1 Complete nonlinear induction motor model

To obtain a complete model for stator flux and mechanical velocity we consider the stator voltages as input $U = [V_{sd} V_{sq}]^T$ and the stator currents as output $y = [I_{sd} I_{sq}]^T$. This model is deduced from a Park transformation and presented in a d-q plan rotating at a velocity w_x. Consequently, the state vector (ζ) consists of the stator current components, stator flux components, mechanical velocity, and finally the resistive torque: With these assumptions, we obtain:

$$\begin{cases} \dot{\zeta} = f(\zeta) + g(\zeta).U \\ y = h(\zeta) \end{cases} \quad (1)$$

$$\zeta = [I_{sd}\, I_{sq}\, \Phi_{sd}\, \Phi_{sq}\, w_m\, C_r]^T .$$

Where $\zeta \in R^n, U \in \widetilde{U} \subset R^m, y \in R^p$. Moreover there is a « physical subset » $\Omega \subset R^n$, which is our domain of interest.

$$f(\zeta) = \begin{bmatrix} b\zeta_1 - (\zeta_5 - w_x)\zeta_2 + a_1\zeta_3 + a_2\zeta_4\zeta_5 \\ (\zeta_5 - w_x)\zeta_1 + b\zeta_2 - a_2\zeta_3\zeta_5 + a_1\zeta_4 \\ -a_3\zeta_1 + w_x\zeta_4 \\ -a_3\zeta_2 - w_x\zeta_3 \\ a_4\zeta_2\zeta_3 - a_4\zeta_1\zeta_4 - a_5\zeta_6 \\ 0 \end{bmatrix}$$

$$g(\zeta) = \begin{bmatrix} \frac{1}{L_{fs}} & 0 \\ 0 & \frac{1}{L_{fs}} \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \qquad h(\zeta) = \begin{bmatrix} \zeta_1 \\ \zeta_2 \end{bmatrix}$$

$$\beta = \frac{L_m}{L_{fs} L_r}, b = \frac{-\beta.(R_s L_r + R_r L_s)}{L_m}, \ a_1 = \frac{\beta R_r}{L_m} \ a_2 = \frac{1}{L_{fs}}$$

$$a_3 = R_s, a_4 = \frac{3P}{2J_0}P, \ a_5 = \frac{P}{J_0}, w_m = P\Omega_m \quad (2)$$

R_s, R_r, L_{fs}, L_r P, Ω_m are respectively the stator resistance, rotor resistance, total leakage inductance, rotor inductance, the number of pairs of poles and the mechanical velocity.

2.2 Luenberger Observer and Open Loop estimation

The complete discrete time model of the machine is deduced from system (1) by discrimination to the first order approximation:

$$\begin{cases} \zeta_{k+1} = \zeta_k + T_e\dot{\zeta}_k = f_d(\zeta_k, U_k) \\ Y_k = h(\zeta_k) = C_k.\zeta_k \end{cases} \quad (3)$$

Indices *k* and *k+1* refer to the variable values at t_k and t_{k+1} respectively. Before applying the Luenberger estimation procedure, the nonlinear model (3) must be linearized by calculating the following Jacobians (5). The linearized model is presented by (4):

$$\begin{cases} \zeta_{k+1} = f_d(\zeta_k, U_k) = \hat{A}_k\zeta_k + \hat{B}_k U_k \\ Y_k = h(\zeta_k) + V_k = C_k.\zeta_k \end{cases} \quad (4)$$

$$\hat{A}_k = \left.\frac{\partial f_d}{\partial \zeta}\right|_{\zeta_k = \hat{\zeta}_k} \quad \hat{B}_k = \left.\frac{\partial f_d}{\partial U}\right|_{\zeta_k = \hat{\zeta}_k} \quad C_k = \left.\frac{\partial h}{\partial \zeta}\right|_{\zeta_k = \hat{\zeta}_k} \quad (5)$$

The estimation by placing poles consists of two phases. First, the state is predicted according to the model given in (4).

$$\begin{cases} \hat{\zeta}_{k+1/k} = f_d(\hat{\zeta}_{k/k}) \\ \hat{Y}_{k+1/k} = h(\hat{\zeta}_{k/k}) \end{cases} \quad (6)$$

Subsequently, this prediction is corrected by injecting the output estimation error:

$$\hat{\zeta}_{k+1/k+1} = \hat{\zeta}_{k+1/k} + K_{k+1}(Y_{k+1} - \hat{Y}_{k+1/k}) \quad (7)$$

The gain "*K*" is computed with the aid of the "place" control by Matlab, specifying the poles which we take to be negative real. For more details on this estimator see [16].
Finally, the Open Loop method for state estimation consists only of the first phase of the Luenberger method, that is to say without any correction of the state.

2.3 High Gain Observer

Assume that the system (1) is observable. Near a regular point there exists a local diffeomorphism:
$x = \Phi(\zeta) = (h_1(\zeta), ..., l_f^{\rho_1 - 1} h_p(\zeta), ..., h_p(\zeta), l_f h_p(\zeta), ...)^t$ This determines a local pyramidal coordinate system in which the system (1) takes locally the form:

$$\begin{cases} \dot{x} = Ax + \varphi(x, u) \\ y = Cx \end{cases} \quad (8)$$

Where:

$$A = \underset{k=1,\dots,p}{bloc-diag}(A\rho_k),\; A_{\rho_k} = \begin{bmatrix}0 & 1 & 0 & 0\\ . & . & . & 0\\ 0 & . & 0 & 1\\ 0 & . & 0 & 0\end{bmatrix} \in R^{\rho_k x \rho_k}$$

$$C = bloc-diag\,(C\rho_k),\; C\rho_k = (1\,0\,..\,0) \in R^{1x\rho_k}$$

$k=1..p.$ (9)

The estimation techniques of the High Gain Observer involve fixing a significant High Gain on the linear part in order to hide the effects of the nonlinear part of the system. For sufficiently small T>0, the system (10) is an exponential observer for the system (8).

$$\dot{\hat{x}} = A\hat{x} + \varphi_{(\hat{x},u)} + \Lambda^{-1}{}_{(T,\delta)} K(y - C\hat{x}) \qquad (10)$$

with

$$\Lambda_{(T,\delta)} = \begin{pmatrix} T^{\delta_1}\Delta_1(T^{\delta_1}) & & \\ & . & \\ & & T^{\delta_p}\Delta_p(T^{\delta_p}) \end{pmatrix} \quad \Delta_k(T^{\delta_k}) = \begin{pmatrix} 1 & & & \\ & T^{\delta_k} & & \\ & & . & \\ & & & T^{\delta_k(\rho_k-1)} \end{pmatrix}$$

$$K = \underset{k=1,\dots,p}{bloc-diag}\,([K\rho_k]_{\rho_k *1}) \qquad (11)$$

δ_i positive integers to be determined, such that, for each block K_{ρ_k}, the matrix $(A_{\rho_k} - K_{\rho_k} C_{\rho_k})$ has all its eigenvalues with strictly negative real part. For more details on HGO see [2].

3 Experimental results

The experimental tests were carried out using the following equipment (see Fig. 1):

1. Motor: 220/380 V; 50 Hz; 1.1 kW; P=2.
2. Electrical parameters of the motor: R_s=11 Ω, R_r=3.75 Ω, L_{fs}=0.04H, L_r=0.47 H
3. Three voltage sensors (LEM)
4. Three current sensors (LEM)
5. An incremental encoder position sensor (2048-point).

The measured signal-sampling period is 0.7 ms (1428 Hz). The detection tests were performed with the equipment described above, first using an undamaged motor, and then one with one broken bar. In each case three different levels of load were used: full, medium and low, which correspond respectively to 100%, 60% and 22% of the nominal torque.

3.1 Estimation of the mechanical velocity and stator flux components.

Figures 2 and 3 compare the mechanical velocity estimated by ELO4, HGO and the Open Loop method with actual measured velocity for a fault-free motor running with two load levels (full and low). We notice that methods using a correction step have two advantages over the Open Loop method:

1- Faster response time in estimating the mechanical velocity (about 0.05 seconds for observers, and about 0.3 seconds for the Open Loop).

2- Smaller velocity estimation error. In an Open Loop this error can be as high as 16 rad/sec at full load, while it is about 0.5 rad/sec for the Extended Luenberger Observer and the High Gain estimation method.

The flux components are estimated in the synchronous frame rotating at 50 Hz. In this frame the stator components have low dynamics, which facilitates their estimation. Fig.4 and Fig.5 show the estimated stator flux modulus with respect to the synchronous frame, computed using the Open Loop, ELO and HGO for a motor with one broken bar running at two load levels (full and low). The stator flux components using the Open Loop estimation method undergo significant fluctuations for about 0.3 seconds before reaching stability, unlike the stator flux modulus estimated using the Luenberger Observer or the High Gain Observer. In addition we notice that at full load the stator flux modulus estimated by the Open Loop has a skew in comparison to that estimated by ELO or HGO.

3.2 Spectral analysis of the electromagnetic torque

Previous studies as in [10] have shown that rotor defects have an influence on the expression of the instantaneous electromagnetic torque. The spectrum of this instantaneous electromagnetic torque contains a signature related to the mechanical fault. Broken rotor bars give rise in the torque's spectrum to a component of frequency « f_d =2*sf*» relative to the fault, "*f*" being the fundamental frequency and "*s*" the slip.

The electromagnetic torque is normally calculated from stator flux and stator currents. In our case the stator flux components are estimated by observers, and consequently an estimated EMT can be calculated using the following formula:

$$\hat{C}_{em} = \frac{3}{2} P\left(\hat{\Phi}_{sd} I_{sq} - \hat{\Phi}_{sq} I_{sd}\right) \qquad (12)$$

$\hat{\phi}_{sd}, \hat{\phi}_{sq}$ are the estimated components in the d-q plane.

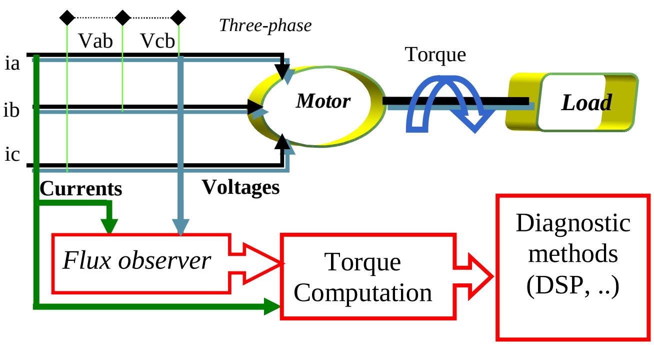

Fig.1. Experimental setup

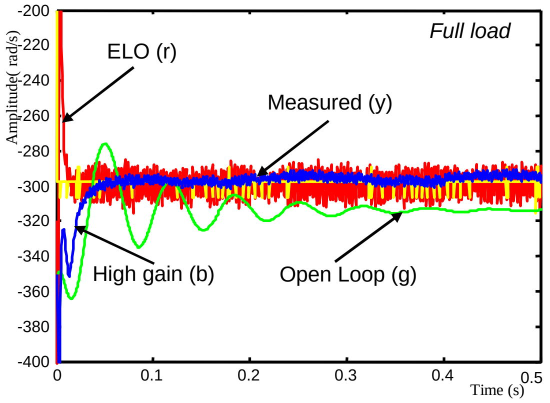

Fig.2. Comparison between estimated and measured mechanical speed. Fault-free motor (full load)

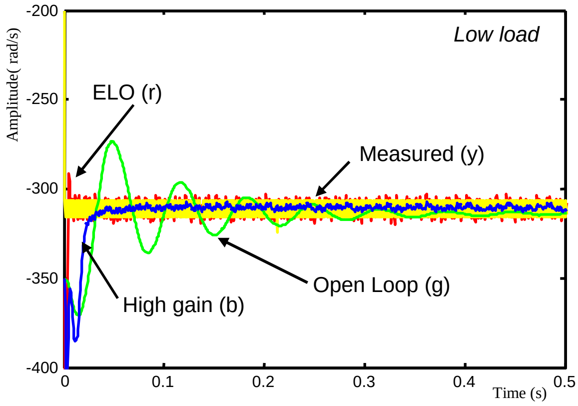

Fig.3. Comparison between Estimated and measured mechanical velocity. Fault-free motor (low load)

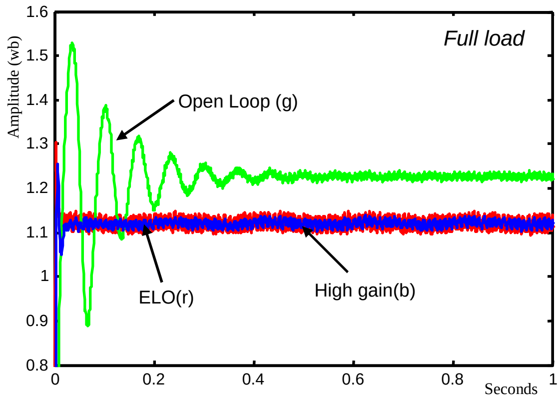

Fig.4. Comparison between estimated stator flux modulus with respect to the synchronous frame: Open Loop, ELO and High Gain methods (full load)

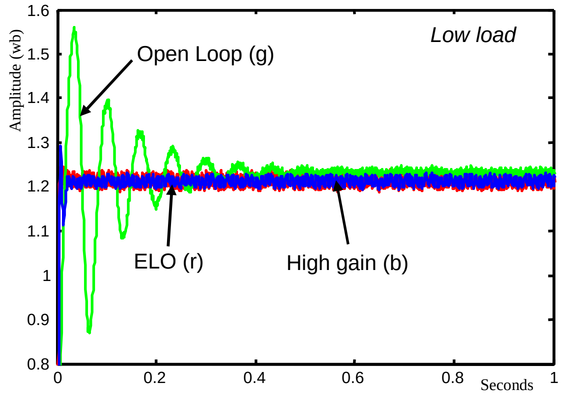

Fig.5. Comparison between estimated stator flux modulus, referred to the synchronous frame: Open Loop, ELO and High Gain methods (low load).

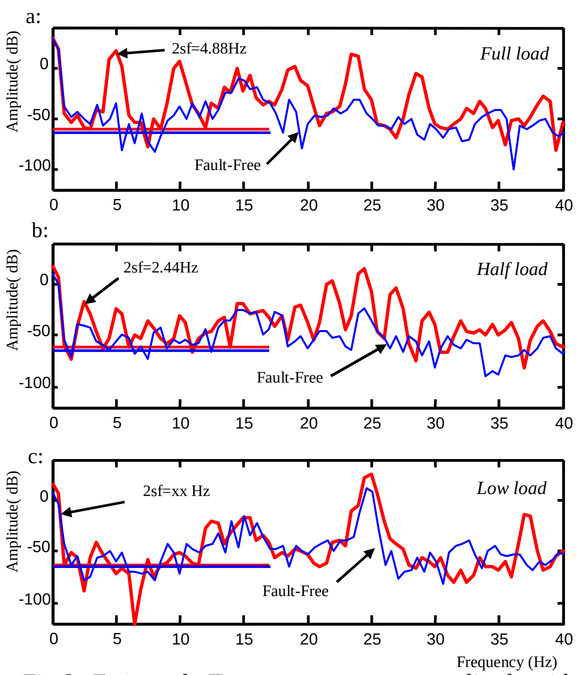

Fig.6 Estimated Torque spectrum normalized with respect to its mean value calculated from stator flux in an Open Loop (Thick line: broken bar, thin line: fault free) for load levels: a. Full, b. Medium, c. Low

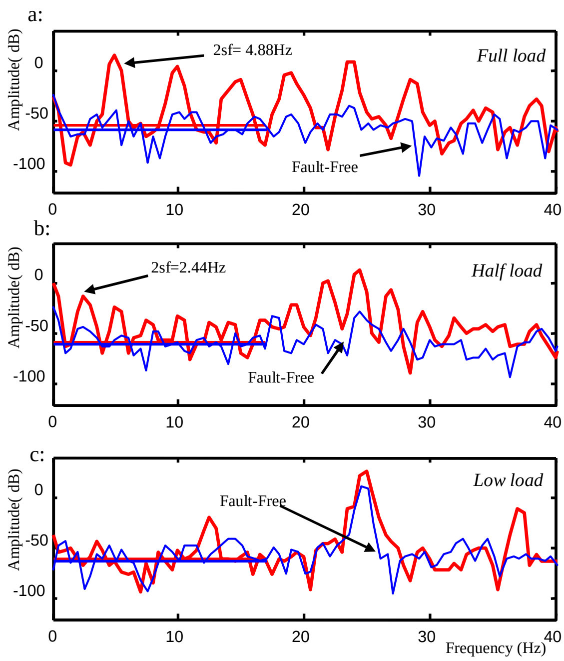

Fig.7 Estimated Torque spectrum normalized with respect to its mean value calculated from stator flux by ELO (Thick line: broken bar, thin line: fault free) for load levels: a. Full, b. Medium, c. Low

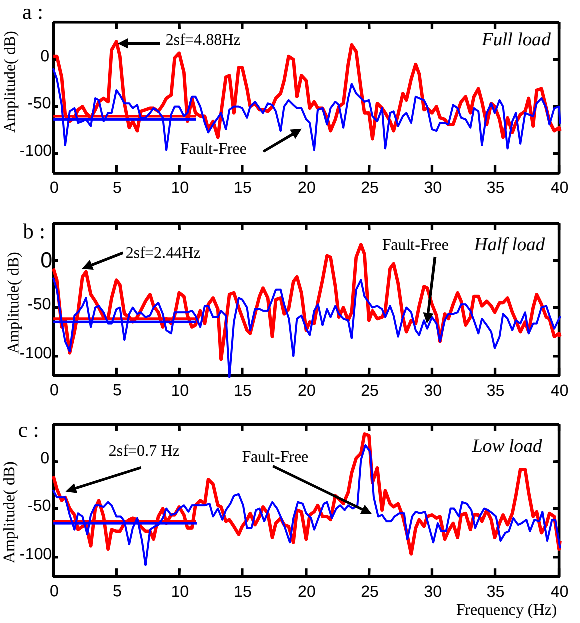

Fig.8. Estimated torque spectrum normalized with respect to mean values, computed from estimated rotor flux by HGO, for load levels: a. full, b. medium, c. low. (Thick line: broken bar, thin line: fault free)

Figures (6a, 6b, 6c), (7a, 7b, 7c), (8a, 8b, 8c) show the EMT spectrum (in dB) computed from the estimated components by the Open Loop method, the Luenberger Observer and the High Gain Observer respectively. Each of these figures compares the EMT spectrums for a fault-free motor (thin line) and a motor with one broken bar (thick line). The comparison is performed for three different load levels : “a” for full load, “b” for half load and “c” for low load. With the Open Loop and ELO estimation methods the fault characteristic frequency “$f_d=2sf$” does not appear at low loads. Fig (6a, 6b, 7a, 7b, 8a, 8b) reveal the existence of spectral peaks at 4.88 Hz and 2.44 Hz for full and medium loads respectively. Notice that only the method based on the High Gain Observer reveals the existence of spectral peaks at 0.7 Hz at low load (fig. 8c).

3.3 Comparison of several methods

Studies as in [10,14] have shown that the amplitude of the fault characteristic components is directly linked to the severity of the fault. A criterion “R” is used to represent the ease of detection and the average of the fault characteristic amplitude; this criterion is calculated by equation (14) as follows.

$$R = \frac{(P_S - Minl) + (P_S - Minr)}{2} \quad \text{in dB} \qquad (14)$$

P_s is the amplitude of the fault characteristic frequency. *Minl* and *Minr* are the left and right peaks respectively having minimum amplitudes around the fundamental peak, as fig.9 clearly shows.

The experimental results are presented in Table 1. The mean value of the comparison criterion « R » for the three different load levels reflects the performances of the different methods in detecting a rotor fault. In general, as shown by mean values of the “R” criterion, methods that make use of a correction step in flux estimation give a better signature for the detection of a broken rotor bar.

The ELO method shows great potential and gives the best results at high load levels. The HGO method is highly effective in detecting broken bars at low to medium load levels. Fig.10 shows the comparison criterion for the three levels of load.

4 Conclusion

This paper has described two new non-invasive approaches for the detection of rotor imperfections by spectral analysis of electromagnetic torque using two stator flux estimators without any speed sensors installation. An Extended Luenberger Observer and a High Gain Observer are applied to the complete order model of the induction machine. Experimental results using real electrical signals show the significance of the ELO and the HGO in estimating the electromagnetic torque, and consequently in detecting mechanical abnormalities in a motor.

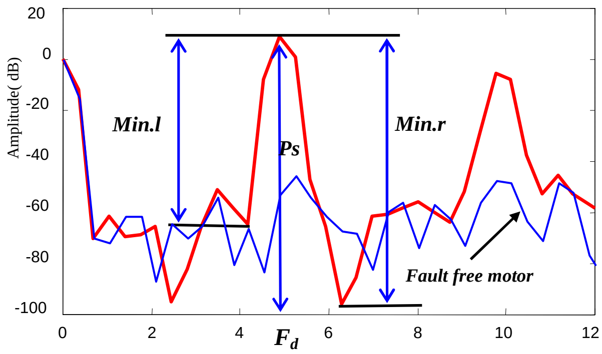

Fig.9 Comparison criterion “R” computation.

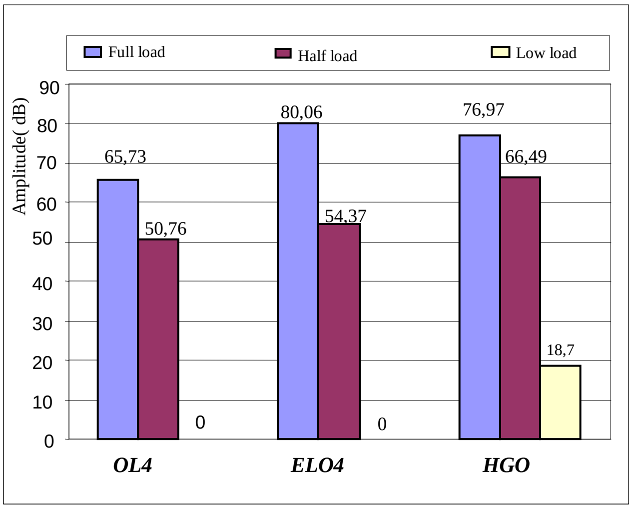

Fig.10 Comparison criterion “R” function of load levels and estimation methods

Methods	**Load**	***Min.l***	***Min.r***	***Ps***	**Comparison Criterion (R)**	**Mean value (R)**
E.M. torque computed from estimated stator flux, using OL4 synchronous frame	Full	-42.9	54.2	17.16	65.73	38.83
	Half	-72.8	63.7	-17.5	50.76	
	Low	X	X	X	0	
E.M. torque computed from estimated stator flux, using ELO4 synchronous frame	Full	-73	55.4	15.86	80	44.79
	Half	-63.5	69.7	-12.23	54.37	
	Low	X	X	X	0	
E.M. torque computed from estimated stator flux, using HGO synchronous frame	Full	-44.7	73.2	18	76.97	54.05
	Half	-96.2	-62	-12.6	66.49	
	Low	-40.5	70.5	-36.8	18.7	

Table 1 Amplitude for specific frequencies & comparison criterion (dB)

We have shown that the ELO and the HGO methods can lead to more effective detection of rotor faults then the Open Loop estimation method at all load levels. The High Gain Observer has shown its potential for detecting rotor abnormalities at low to medium loads, while the ELO show great aptitude at full load level. Finally, these methods (ELO, HGO) remain sensitive to variations in certain electrical parameters including rotor resistance and rotor inductance. Currently we are concentrating on the sensitivity of these two approaches to fault detection, with the aim of avoiding the false alarms that can be produced by natural variations in electrical parameters.

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