Comprehensive Induction Motor Fault Diagnosis Using Extremum Seeking Control

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***Abstract*- This paper proposes a method based on Extremum Seeking Control (ESC) for the detection of four major types of faults that occur in induction motors. The proposed method does not require additional sensors and does not depend on the model of the induction machine. By combining ESC and time-frequency analysis methods used for analyzing the motor current signature, the proposed method outputs the type of fault which occurred on the induction motor. The method proposed is highly robust against noise and is able to detect fault components that are very close to the fundamental frequency, even when the motor is lightly loaded. Simulations show the validity of the proposed fault detection method on the broken rotor fault type, as a case study.**

I. Introduction

Induction motors are the workhorse of industrial and manufacturing processes. It is of immense importance to maintain the health of the induction motors to ensure smooth, uninterrupted and normal operation of such processes. Many factors such as regular wear and tear, over-rated loads and uncertain events play a role in exacerbating major faults in induction motors. To avoid or circumvent unexpected downtime and unsafe operation, fault detection and diagnostic methods must be implemented.

To aid with fault detection and diagnostics, a handful of sensors could be used to collect measurements from an induction motor. Literature contains methods that rely on stator voltages and currents, air-gap and external magnetic flux densities, rotor position and speed, output torque, internal and external temperature, case vibrations, and others. On the other hand, a failure monitoring system must be used to monitor a variety of motor failures [1]. The four main types of induction machine faults that are actively discussed in the literature are: air-gap eccentricity fault, bearing fault, broken rotor bar fault and stator short-winding fault. Many different techniques for fault detection and diagnosis are discussed in the literature. The methods can be categorized into three main branches: time-domain methods, frequency-domain methods and a hybrid of time and frequency methods. A thorough evaluation of the literature and comparison of the proposed method with state of the art wavelet-based and machine-learning-based motor fault diagnosis is shown in [2].

ESC has been explored in some literature for fault diagnosis, degradation, and fault-tolerance applications [3]. For example, internal resistance change in photovoltaic arrays is tracked using ESC [4]; this resistance is an indicator of array degradation. Another application is in fault-tolerant cooperative control as demonstrated in [5, 6]. However, the only known prior work that prepared for extremum-seeking control in induction machine is [7], but it did not include any ESC implementation plans.

In this paper, a new time-frequency method is proposed for fault detection and diagnosis. The method monitors only the motor current, which is readily available in most drives, and is capable of detecting four major types of faults. The method is robust against noise and motor parameter variations, since it does not rely on the model of the motor. It has satisfactory performance even when the motor is lightly loaded. Extremum Seeking Control (ESC) is used as an optimization tool for the purpose of maximizing the cost function, which happens to be at the fault frequency. By utilizing short-time Fourier transform in conjunction with ESC, the proposed method outputs the fault frequency. To be able to detect faults when the motor is lightly loaded, the proposed method uses (1) a time-varying notch filter to remove the fundamental component of the current and (2) a window-size selection algorithm. A variable window size also helps in obtaining the optimal time-frequency resolution.

II. Fault Types

Faults in induction motors generate abnormal features in different domains. Fault-revealing features can be detected from voltage, current, magnetic, vibration and acoustic waveforms, to name a few. Among all the feedback signals, stator current of induction motors is the most widely used, since current sensors are relatively inexpensive and they are already installed motor drive systems for control purpose. The four main types of faults that highly discussed in the literature are: air-gap eccentricity fault (EF), bearing fault (BF), broken rotor bar fault (BRBF) and stator short-winding fault (SSWF). The fault characteristic frequency components of these faults in the stator current spectrum are summarized in Table 1 [2]. f_e is the electrical supply frequency in Hz, s is the motor slip, P is the number of pair poles, k is a non-negative integer, N_{rs} is the number of rotor slots, N_{re} is the order of rotating eccentricity, N_{sm} is the order of stator magnetomotive force harmonics, and N_{br} is the number of bearing rolling balls. For inner race faults, α=0.6 and $\gamma=k_3$. For outer race faults, α=0.4 and $\gamma=k_4$. k_1 , k_2, ..., k_6 are constants and depend on the machine's geometry and/or ratings.

III. Proposed Methodology

A. Extremum Seeking Control

Extremum-seeking control (ESC) is a form of adaptive control. It has guaranteed convergence and stability under a set of well-defined conditions. Extremum seeking can be used to track local maxima of an objective function, despite varying system parameters, nonlinearities and disturbances. ESC can be seen as a perturb and observe method where a sinusoidal perturbation is injected in the actuation signal with the purpose of optimizing an objective function. The objective function is computed based on values obtained from sensor measurements. Figure 1 describes the ESC architecture. The input perturbation is used to estimate the gradient of the objective function and direct the average actuation signal in the direction of the optimizing value [8].

Table 1 - Fault types and related equations

Fault type	**Fault characteristic frequency component**	
Eccentricity	Dynamic and mixed EF	$f_{fault} = f_e\left(1 \pm \frac{2k_1(1-s)}{P}\right)$
	Principal slot harmonics	$f_{fault} = f_e\left(\frac{2(k_2N_{rs} \pm N_{re})(1-s)}{P} \pm N_{sm}\right)$
Broken Rotor Bar	$f_{fault} = f_e(1 \pm 2ks)$	
Stator Short Winding	$f_{fault} = f_e\left(\frac{2k_5(1-s)}{P} \pm k_6\right)$	
Bearing	$f_{fault} = f_e + \alpha\gamma N_{br} f_{rm}$	

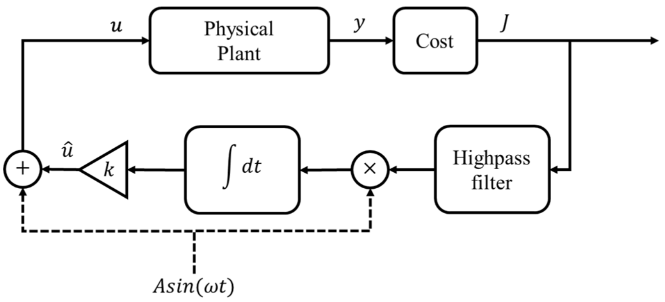


Figure 1. ESC block diagram

As shown in Figure 1, a sinusoidal perturbation, $A\sin(\omega t)$ is added to the input $\hat{u}$ to perturb the system. The output y of the system, which is sinusoidal, is used to calculate the cost function J in a minimization application. By high-pass filtering, a zero-mean output perturbation is obtained, which is demodulated by the same input perturbation resulting in the signal. The demodulated signal is integrated and multiplied by a constant to find the best guess $\hat{u}$ for the optimizing input u.

B. Short-Time Fourier Transform

Signals with non-stationary frequency content should have their content characterized at certain windows in time. The discrete version of the Short Time Fourier Transform (STFT) is a mathematical tool that achieves this goal [9]. It is defined as:

$$X_n(\Omega) = \sum_{m=-\infty}^{+\infty} T_n(x)w[n-m] = \sum_{m=-\infty}^{+\infty} x[m]e^{-j\Omega m}w[n-m]$$

$$T_n(x) = x[n]e^{-j\Omega n}$$

where Ω is a discrete frequency, $x[n]$ is the input signal at time n, $w[n]$ is the window function of size M, and $X_n(\Omega)$ is the discrete time Fourier transform (DTFT) of the windowed version of $x[n]$.

C. Proposed Method

The proposed method combines both the ESC and the STFT for fault detection and diagnosis. The method is able to detect the fault by searching for the frequency component in the sensed current waveform based on the relations discussed in Section II. By choosing the type of fault for analysis and supplying the parameters required to obtain the fault frequency f_{fault}, the proposed method uses f_{fault} as an initial estimate for the fault frequency. If the ESC converges with a magnitude higher than a certain threshold, this signals that a fault exists. A high-level overview of the proposed scheme used to detect a BRBF is depicted in Figure 2. f_0 is the fundamental frequency and ω_r is the rotor mechanical speed.

To be able to detect fault frequencies at lightly loaded conditions, that is when the motor is running at low slip, the method uses 1) a time-varying notch filter to remove the fundamental component of the current, and 2) a window size selection algorithm. The goal of the notch filter is to eliminate the dominating side lobes found on both sides of the fundamental component due to windowing. By obtaining the fundamental frequency from the motor drive controller, the notch filter's poles and zeros are calculated for a fixed 3dB bandwidth.

During a fault, the objective function of the ESC that needs to be maximized, requires to be a convex function. The convexity of the cost function $J(\Omega)$ for frequencies near the fault frequency of interest can be ensured by choosing the cost function as,

$$J(\Omega) = X_n(\Omega) = \sum_{m=-\infty}^{+\infty} x[m]e^{-j\Omega m}w[n-m]$$

$$s.t.\ \Omega_{fault} - \Delta < \Omega < \Omega_{fault} + \Delta$$

$$x[n] = i_a[KT_s] = i_a[n]$$

where T_s is the sampling period, K is an integer and $x[n]$ is the sampled current of the motor. The window size will be chosen in real-time based on the required frequency resolutions, the fault type, and motor slip. This will be analyzed and discussed in the final paper. To prove the convexity of the cost function near the fault frequency of interest, it can be shown that during a fault at time $n=n_1$, which results with an added frequency component of f_{fault}, the STFT of the signal can be presented as:

$$X_{n_1}(\Omega) = \frac{1}{2\pi}X(\Omega) *_{(2\pi)} \left(W(\Omega)e^{-j\Omega n_1}\right)$$

$$s.t.\ \Omega_{f_{fault}} - \Delta < \Omega < \Omega_{f_{fault}} + \Delta$$

where Δ is dependent on the window size. For a Gaussian window type,

$$w[n] = \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{n^2}{2\sigma^2}} \leftrightarrow W(\Omega) = e^{-\frac{(\Omega\sigma)^2}{2}}$$

$$\left|X_{n_1}(\Omega)\right| = \frac{1}{2\pi}e^{-\frac{(\Omega\sigma)^2}{2}}$$

Therefore, $|X_{n1}(\Omega)|$ is a convex function near the fault frequency. Similar arguments can be held for other popular window functions such as Hamming, Hanning, etc. To reduce the computational complexity of the proposed method, the DFT block can be replaced with a Goertzel filter [10].

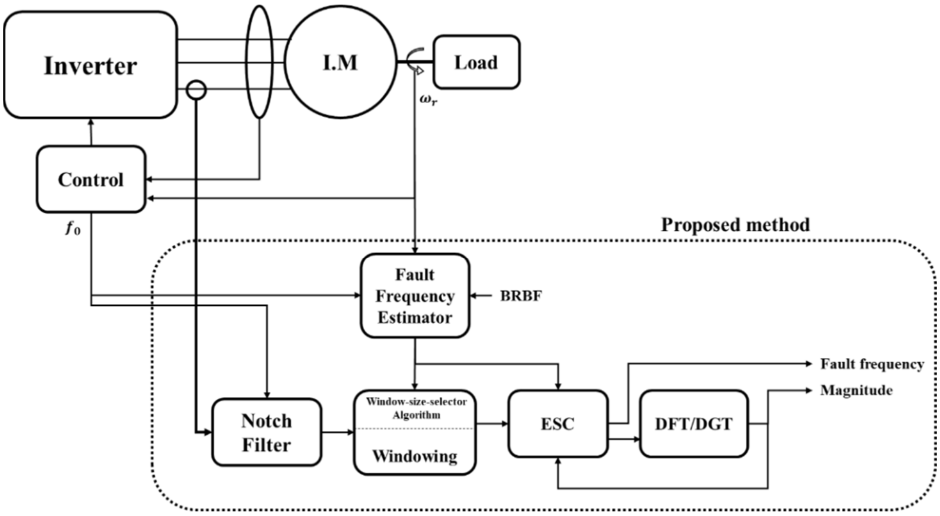


Figure 1. Proposed scheme for detecting BRBF as an example; other faults use a similar scheme

Compared with time-frequency methods found in the literature, the proposed method is able to detect fault frequencies even when the motor is lightly loaded, while using less computationally complex techniques.

IV. RESULTS

To assess the proposed method, a simulation was run using a 4 pole, 5.4 HP induction motor connected directly to a three-phase 480V, 50Hz voltage source. The load torque applied and the rotor speed along with the synchronous speed is shown in Figure 2. The current of phase ‘a’ is captured using a current sensor. A broken rotor bar fault was injected at t=2s.

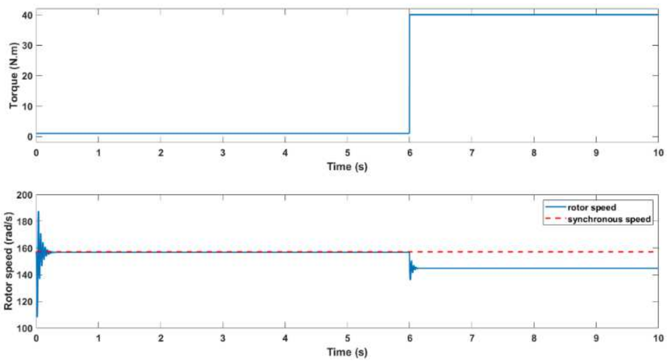
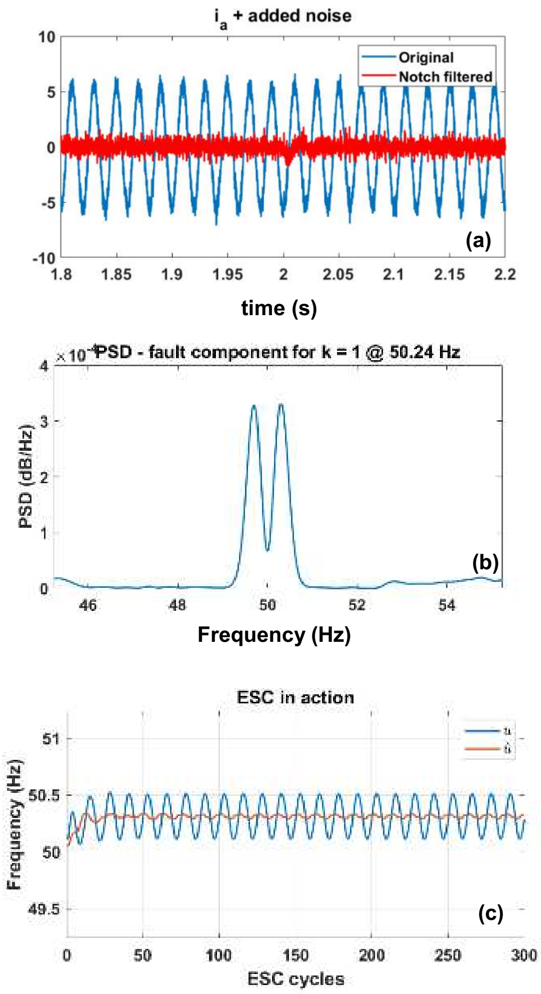


Figure 2. Torque and Speed Responses

The raw current and the filtered current signals are shown in Figure 3 along with the power spectrum density (PSD) of the current waveform after the notch filter. The fault component is clearly visible at 49.76 and at 50.24 Hz. To be able to achieve the required accuracy in the frequency domain, a window size of 3 seconds was selected by the window-size selection algorithm.

Figure 3 also shows ESC in action at low torque, where the ESC takes about 10 iterations to find the fault frequency, found to be at 50.29 Hz. This is very close to the real fault frequency at 50.24 which is calculated based on the slip speed and the equations presented in Section II. The ESC was given an initial estimate of 50.15 Hz to mimic the noisy measurements obtained from the speed sensor, which is used to calculate the motor slip and supply the ESC with the initial seed. As it is shown in the figure, the objective function is maximized at the fault frequency. Input u and $\hat{u}$ are presented in Figure 1, where $\hat{u}$ is the fault frequency.

At high torque, which happens between 6s < t < 10s, fault frequencies with highest amplitude appear at 42.2Hz and 57.8Hz. For this scenario, the window size is chosen to be 1.5s. In Figure 4, the PSD shows the fault frequency with the highest magnitude at 57.8Hz. The ESC is able to find the fault frequency which converges at 57.84Hz. This shows the validity of the proposed method also at high load torques.



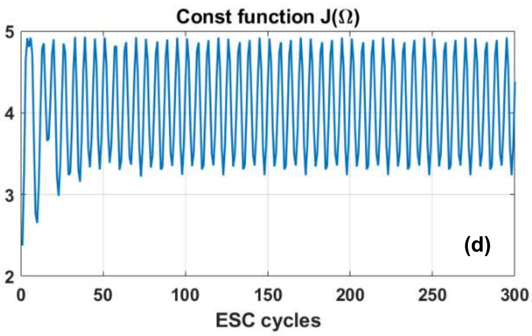


Figure 3 - ESC in action with low torque; (a) i_a is the phase a current in (A), (b) PSD of the fault component, (c) ESC convergence to the fault frequency, and (d) Cost function *J*.

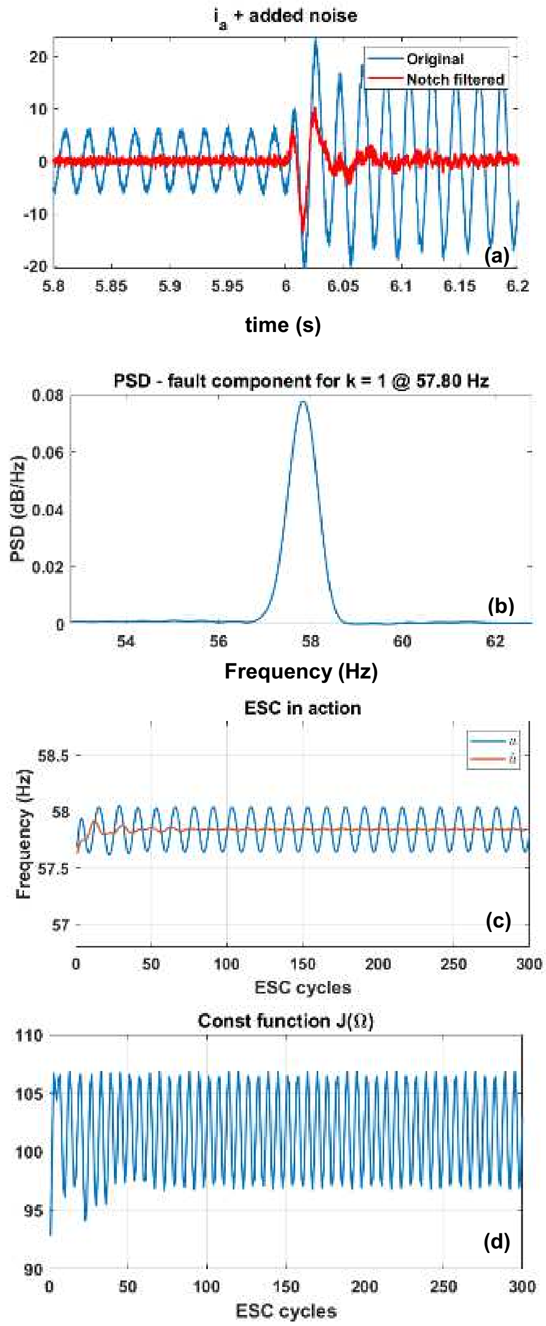


Figure 4 - ESC in action with high torque (a) i_a is the phase a current in (A), (b) PSD of the fault component, (c) ESC convergence to the fault frequency, and (d) Cost function *J*.

V. REFERENCES

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