

# A New Method for Early Detection of Inter-Turn Shorts in Induction Motors

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**Abstract.** This paper presents a novel approach to Motor Current Spectral Analysis (MCSA) for early detection of inter-turn shorts in the stator windings of three-phase squirrel-cage induction motors. This is done by spectral analysis of the stator currents using the Discrete Fast Fourier Transform. For early detection, and to eliminate the effect of changing speeds that tend to mask the characteristic fault frequencies, very short data windows have been used. The deficiencies of DFFT in spectral analysis over short data windows are mitigated by using the Burg method as a signal prediction tool. The short data window is extrapolated to a length over which DFFT provides adequate frequency resolution, enabling the detection of the characteristic fault frequencies which show up in the amplitude spectrum of stator current.

**Keywords:** Motor Current Spectral Analysis, Inter-turn shorts, Discrete Fast Fourier Transform, Short data window, Burg method, Signal prediction.

## 1. Introduction

Motor Current Spectral Analysis (MCSA) is one of the most popular techniques for strategic preventive maintenance. It is widely used for the detection and localization of abnormal electrical and mechanical conditions that indicate, or may lead to, a failure of induction motors [1]-[2]. MCSA focuses its efforts on the spectral analysis of the stator current and has been successfully applied to detect broken rotor bars [3]-[4], abnormal levels of air-gap eccentricity [5], and shorted turns in stator windings [6].

Although a few shorted turns do not inflict a noticeable degradation on motor performance, the problem can easily spread to other turns, ultimately leading to total loss of the turns or even the entire winding [7]. This necessitates early detection of inter-turn shorts in the stator windings, which makes the use of short data windows vital.

The Discrete Fourier Transform (DFT) can be used for detection of inter-turn shorts in induction motors. The Discrete Fast Fourier Transform (DFFT) is an algorithm for fast implementation of the DFT, and has been cited as an effective method for MSCA [9]. However, the DFFT suffers from certain defects that limit its practical use, the most major of which is the requirement of a long data window for sufficient frequency resolution.

This paper presents a novel approach to MCSA for inter-turn short detection using the Discrete Fast Fourier Transform. The central idea is signal prediction using the Burg method to extend the short data window of stator current. At the increased length, the DFFT is able to clearly resolve the characteristic fault frequency peaks associated with stator inter-turn shorts.

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The following sections present the theoretical background behind MCSA, the proposed approach to inter-turn short detection, the experimental results and the conclusions drawn.

## 2. Theoretical Background

### 2.1. Characteristic fault frequencies

Inter-turn shorts in the phase windings of induction motors lead to flow of short-circuit current, which produces a negative MMF [7]. This distorts the net air-gap MMF, introducing harmonics in the stator current at certain characteristic fault frequencies given by [8]:

$$f_{short} = \left\{ \frac{n}{p} (1 - s) \pm k \right\} f_{line} \quad (1)$$

Where  $p$  is the number of pole pairs,  $n = 1, 2, 3, \dots$ ,  $k = 1, 3, 5, \dots$ , and  $f_{line}$  is the line frequency (50 or 60 Hz) respectively.

Peaks at these characteristic fault frequencies can be detected by computing the DFFT of stator current, provided the data window is long enough for sufficient frequency resolution.

### 2.2. The Burg method as a signal prediction tool

The Burg method is a parametric signal-modelling method that uses an auto-regressive (AR) process. It is often used to calculate the DFFT of signals, and is known to produce better frequency resolution than other methods (such as non-parametric or eigenvalue decomposition) for short data records [10]. In this paper, very short data windows (0.5s) have been considered. For this length, even parametric methods do not produce satisfactory frequency resolution with the DFFT.

To resolve this problem, it is proposed that the Burg method be used as a signal prediction tool. First the short-time signal is modelled using the Burg method, which produces the Burg coefficients  $a_k$  as:

$$x[n] = -\sum_{k=1}^p a_k x[n-k] + e[n] \quad (2)$$

Where  $x[n]$  is the  $n$ -th sample of the signal,  $e[n]$  is a zero-mean white-noise process with unknown variance  $\sigma^2$ , and  $p$  is the order of the auto-regressive process, in this case the Burg method.

These coefficients are then used to extrapolate the short-time signal to a longer time window, such that spectral analysis of the extrapolated signal using DFFT produces sufficient resolution.

## 3. Proposed Diagnostic Method

The proposed diagnostic method for inter-turn shorts detection can be summarized by the following steps:

1. DFFT of short-time stator current signal to see if any peaks are visible at or around the characteristic fault frequencies.
2. Extrapolation of short-time stator current signal to create a long data window using the Burg method.
3. DFFT of the long-time current signal.
4. Analysis of the obtained amplitude spectrum for peaks at and around the characteristic fault frequencies.

The experimental data was obtained from [http://laji.univ-poitiers.fr/Diagnost/data\\_essais/Essais](http://laji.univ-poitiers.fr/Diagnost/data_essais/Essais).

The process and results are described in detail below.

### 3.1. Experimental set up

The motor under observation was a three-phase squirrel cage induction motor, rated at 1.1kW, 380V and 50 Hz. The stator currents were measured using three current transducers with Hall effect LEM. The sample time used was 0.7ms. The obtained signals were preprocessed using 4th order Butterworth filters. The motor was operated under the following conditions:

- Healthy stator: low, medium (50%) and full load
- 18 out of 464 (3.88%) turns in phase-a stator windings shorted: low, medium (50%) and full load

Only the phase-a stator current was observed, for a period of 0.5s. The abovementioned steps were carried out. The extrapolation was done up to  $t = 6s$ , using the implementation of the Burg method in the

Signal Processing Blockset of MATLAB. The order of the Burg model chosen was the maximum possible for the 0.5s data-set (715). The next section describes the results obtained.

### 3.2. Results

(A) *Low load*: At low load, the motor was running at a slip of 0.8%. Considering the fifth harmonic of line current (250 Hz), this corresponds to a characteristic fault frequency of 274.8 Hz. Figure 1 (a) shows the amplitude spectrum of phase-a stator current obtained when short-time signal (0.5s) was used, for the healthy as well as the faulty stator. Figure 1 (b) shows the corresponding spectrum for stator current extrapolated to 6s.

It can be seen that the short-time current spectrum suffers from two anomalies. First, the frequency profile at and around the characteristic fault frequency (274.8 Hz) is relatively flat for both the healthy as well the faulty stator. And second, the healthy stator shows higher amplitudes at the said frequencies than the faulty stator, which must not be the case.

In the spectrum obtained from extrapolated current, a sharp peak can be observed close to the characteristic fault frequency, in case of the faulty stator (in green). This is clearly indicative of shorted turns.

(B) *Medium load*: At medium (50%) load, the motor was running at a slip of 2.6%. Considering the fifth harmonic of line frequency, this corresponds to a characteristic fault frequency of 274.35 Hz. Figure 2 shows the spectra obtained from short-time as well as extrapolated current signals, for the healthy as well as faulty stator.

As in the case of low load, the short-time spectrum is misleading and inadequate, while the extrapolated spectrum shows a sharp peak near the characteristic fault frequency. Once again, this clearly indicates shorted turns.

(C) *Full load*: At full load, the motor was running at a slip of 5%. With the fifth harmonic of line current being under consideration, the characteristic fault frequency is 273.75 Hz. The corresponding spectra for short-time and extrapolated current are shown in Figure 3. The short-time current spectrum exhibits a relatively flat profile (indicative of poor resolution), while the extrapolated current spectrum shows multiple peaks around the characteristic fault frequency.

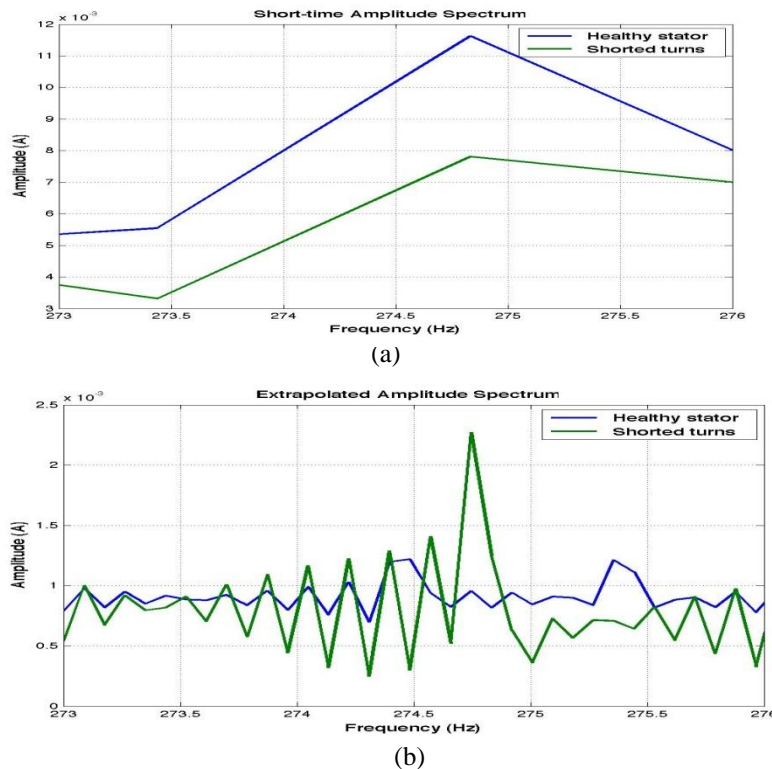
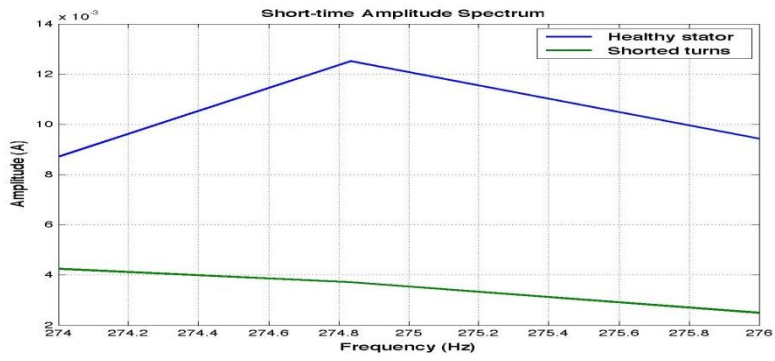
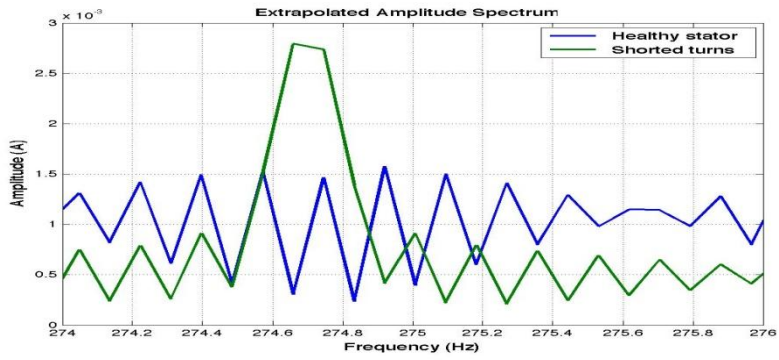


Fig. 1: Amplitude Spectra for (a) short-time and (b) extrapolated stator current for low load

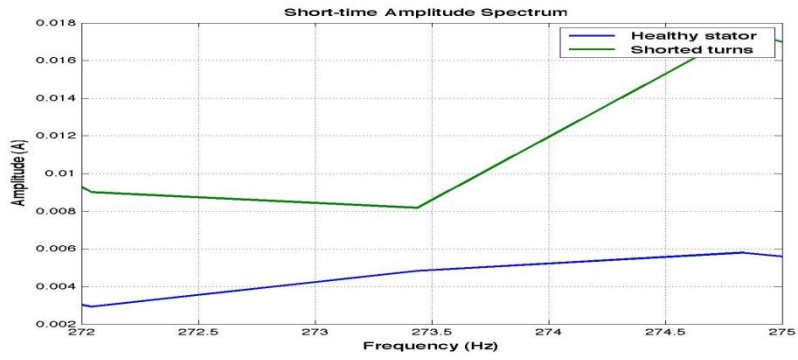


(a)

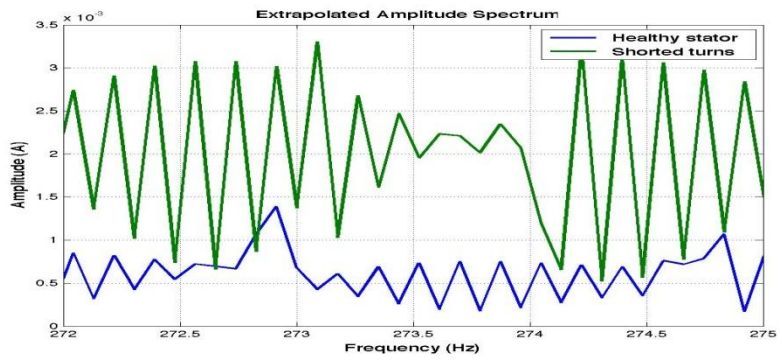


(b)

Fig. 2: Amplitude Spectra for (a) short-time and (b) extrapolated stator current for medium load



(a)



(b)

Fig. 3: Amplitude Spectra for (a) short-time and (b) extrapolated stator current for full load

## 4. Conclusions

The results show that with signal prediction using Burg, computing the DFFT of the stator current produced clear peaks at the characteristic fault frequencies related to inter-turn shorts in stator windings. These peaks are easily distinguishable, being considerably higher in magnitude than those for a healthy stator. DFFT of current data measured over 0.5s (short-time), on the other hand, did not produce reliable results. It may be noted that the spectra being analysed are those of current amplitude, and not power density.

The advantage of the proposed diagnostic method lies in the fact that it uses very short data windows to detect inter-turn shorts. This enables early fault detection and eliminates the effects of speed variations which could mask the characteristic fault frequencies. The computation time involved in the entire process is also small enough for it to be used as an online diagnostic method for fault detection.

As further work, the order of the Burg model used may be calculated using standard techniques to optimize the signal prediction. Also, other techniques for signal prediction may be explored.

## 5. References

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