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Review Induction Motor Mechanical Fault Analysis using DSP Techniques of Stator Current in Frequency Domain

#1Miss Mugdha P. Kulkarni,#2Prof. Saket R. Yeolekar, #3Dr. G. N. Mulay

Abstract

Induction motors are widely used in all the applications. Various electrical and mechanical faults may occur during the working of the induction motor. Fast and reliable diagnosis of the fault is important aspect for smooth and proper working of induction motor. Induction motorstator current monitoring is one approach to avoid the damage to the motor. Digital Signal processing technique based current monitoring is used for the fault analysis. These methods are divided into various domains such as frequency domain, time scale/time-frequency domain and time domain. The paper focuses on various methods of frequency domain analysis such as Chirp-Z transform (CZT), Zoom-FFT (ZFFT), Zoom-MUSIC (Z-MUSIC) and maximum covariance method (MCM). These methods are affected by frequency resolution and spectrum analysis which can change the performance of frequency domain. These methods improve frequency resolution of the spectrum. The methods can be implemented and verified using floating point DSP controller TMS320F2833X.

Keywords:- Induction motor, Current signature, Frequency domain, CZT, ZFFT, Z-MUSIC, MCM, TMS320F2833X.

1. Introduction

Induction motors are widely used in many residential, commercial and industrial applications. Health of the motor is important factor that can affect the life of the motor. Faults in induction motor are classified into mechanical faults and electrical faults. Mechanical faults are classified as bearing faults, eccentricity faults and load faults. According to recent research the percentage occurrence of the faults are as follows. Bearing fault (69%), rotor bar fault (7%), stator windings fault (21%) and shaft related faults (3%)[1]. Earlier day's technologies those are available can be divided into two groupssuch as invasive sensor technology and non-invasive monitoring. In invasive technology, sensor is fixed within the motor to sense irregular behaviour. The major disadvantage of this technology is implantation of the sensor. The cost involved in invasive technique is much more than the non-invasive technology. In non-invasive technique of monitoring, the electrical and mechanical quantities of motor such as current, voltage, flux, torque and speed are used for diagnosis of motor. Stator Current Signature Monitoring is one of the methods of non-invasive monitoring [1]. The studies carried out as per rotating field theory any rotor in symmetry generates a component at $(1-2s)\ f$ in the stator current spectrum with assumption of constant speed where s is the slip and f be the frequency of the supply without this assumption (1+2s) f appears in the stator current is confirmed by the experiment [7]. In condition monitoring, the continuous evaluation of health of the motor is carried out. Digital signal processing techniques (DSPT) can be obtained to detect and analyze these faults. DSPT deal with the discrete time signal. These techniques are classified into different domains such as frequency domain, time-frequency or time scale domain and time domain. In frequency domain, the signal is considered as a random process. Time scale/time frequency domain methods are used when time evolution of frequency component in a non stationary signal is required. When information regarding amplitude or phase of the signal is required it is useful to use methods included in time domain [2]. This paper mainly focuses on Mechanical faultsuch as bearing fault of motor. It uses methods in frequency domain such as CZT and Z-MUSIC to analyze these faults.

2. Frequency Domain Environment

Factors that affect the performance of frequency domain analysis are frequency resolution and spectrum analysis. To avoid spectrum leakage suitable window function is used. For consistent diagnosis, frequency resolution is an important factor for any accurate frequency tracking in a spectrum [2]. It is very much necessary to improve the frequency resolution of a spectrum. In frequency domain various methods are available which improves the frequency resolution. Such methods can be listed as Discrete Fourier Transform (DFT),

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Fast Fourier Transform (FFT), ZFFT, CZT, Z-MUSIC, MCM etc. Any continuous wave form can be converted in to discrete co-ordinates, when Fourier transform is calculated only at discrete points then it is called as DFT. AlthoughDFTisthemoststraight forwardmathematical procedure for determining frequency content ofa time domain sequence, it is very inefficient.Asthenumberof pointsintheDFTis increasedtohundredsorthousands,the amountofnecessarynumbercrunchingbecomesexcessive. Hence another method called FFT is developed. FFT is nothing but the computationally efficient way to perform discrete Fourier transform. But in FFT, the information regarding time at which the event is occurring cannot be detected. For analysis of faults in the motor, the main requirement is of specific frequency band and hence the ZFFT technique is taken in to consideration. ZFFT focuses only on special frequency bins and reject all other frequencies. Using ZFFT features like reduction in computation time, saving of memory space, accuracy in specified frequency range can be obtained. The ZFFT focuses on frequency bandwidth of a signal by sampling the signal andthen shifting it to 0 KHz frequency, the signal is then filtered and decimated to view it with high frequency resolution. CZT is also power full technique to detect the frequencies in particular bandwidth range and it doesn't change the data sequence. CZT has a base of Z-transform in which the frequency range is selected as any arbitrary number segment in the Z plane. CZT is very effective technique in narrow frequency band range for non-stationary signals [3]. Zero-padding techniqueis also improves the frequency resolution of spectrum by adding number of zeros to discrete signal which artificially increases the data length of the signal.

The diagnosis of induction motor can be done using another method called as MUSIC, but it is very difficult to apply this method in real time systems because of its high computational time. The zoom technique and MUSIC arecombined toform a new technique called ZMUSIC. ZMUSIC reduces the computational time.

Maximum covariance method (MCM) is another technique which is based on the covariance between the input signal and the reference signal in time domain. When good frequency resolution and large bandwidth is required MCM takes long computational time. MCM and ZFFT methods are combined to enhance the diagnostic reliability [4]. MCM technique has been used to accurately calculate the slip and grid frequency of the rotor and the ZFFT technique concentrate on the side band frequencies which are present around the grid frequency in the current spectrum.

3. Rotor Fault Diagnosis

About 50 to 60 % failures in induction motors are because of mechanical faults. Out of which 40 to 50% motors failures are because of bearing faults [1]. The bearing faults can be classified as outer race defect, inner race defect, ball defect and train defect. Figure1 shows all types of bearing faults,

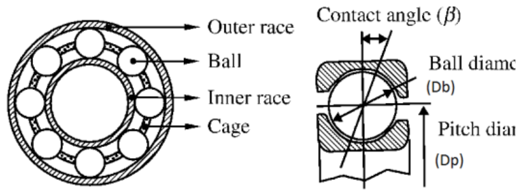

FIGURE 1: BEARING FAULTS

Bearing faults causes vibrations in machine. The vibration frequency is a characteristic frequency for each defect. These fault frequencies are given as [3],

$$Fv = Fcf = \frac{1}{2} fr(1 - \frac{Db}{Dp} cos\theta) .... [1]$$

$$Fv = Forf = \frac{Nb}{2} Fr(1 - \frac{Db}{Dp} cos\theta) .... [2]$$

$$Fv = Firf = \frac{Nb}{2} Fr(1 + \frac{Db}{Dp} cos\theta) .... [3]$$

$$Fv = Forf = \frac{Dp}{2Db} Fr(1 - \left(\frac{Db^2}{Dp^2}\right) cos^2\theta) .. [4]$$

The vibration frequencies for cage fault, outer race fault, inner race fault, ball fault are given by equations (1),(2),(3) and (4) respectively. Where, Nb is the number of balls, Db is ball diameter, Dp is ball pitch diameter, fr is rotor speed and θ is the ball contact angle. The mechanical vibrations caused by these faults can create air gap eccentricity. Hence, the characteristic current frequency given as, in which f1 is a electrical supply frequency, m is 1, 2 ,3,.........and fv is one of the four characteristic frequency.

$$Fcv = |f1 \pm mfv| .... [5]$$

These bearing faults can be detected using Z-FFT technique or combine use of CZT and Z-MUSIC. The combine use of CZT and Z-MUSIC improves frequency resolution which is the basic need in frequency domain analysis. CZT is applied to signal to evaluate the fundamental frequency of current. After obtaining the fundamental frequency component it is turned into dc component by shifting it to 0Hz. The Z-MUSIC technique is then applied to detect the characteristicfrequencies of

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bearing faults by zooming the particular frequency range.

A. CZT

The CZT algorithm evaluates signal z-transform on a spiral path, unlike FFT, which uses a circular way with unitary radius. A general definition for CZT of n points evaluated by means of the entire set of N sampled points of the signal x is [3],

$$X(Zk) = \sum_{n=0}^{N-1} x(n)A^{-n}W^{nk}$$

Where, k= 0, 1, and 2........N-1................. [6]

Where,

$$W = W0.e^{-j\varphi} \text{ .... [7]}$$

And,

$$A = A0.e^{+j\varphi} \text{ .... [8]}$$

In the particular condition in which A0 =1 and W0=1, the CZT returns the same result as the FFT (the spiral contour becoming a unit circle), But it is limited to a frequency band Fw=[Fmin; Fmax]. Consequently the CZT, unlike FFT, does not require the analysis of the entire spectrum with the same resolution. The spectrum resolution for the CZT algorithm is,

$$\Delta Fczt = \frac{Fw}{N} = \frac{Fw}{Fs.T} \text{ .... [9]}$$

In this case, the CZT does not depend only on the observation window, unlike classical methods (FFT, Welch, etc.), but on the ratio between the special window analyzedFw and the sampling frequency Fs.

CZT technique is employed to evaluate the fundamental frequency of the current and when the fundamental component is obtained then turn it to DC component by shifting it to 0Hz.Shifting is done according to the translation of discrete Fourier transform,

$$X(n) \leftrightarrow X(F.\frac{N}{Fs}) \text{.................................... [10]}$$

$$\exp\left(-j\frac{2\pi n}{Fs}\ Fshift\right)\ X(n) \overset{1}{\leftrightarrow} X((F - Fshift)\frac{N}{Fs} \text{ .... [11]}$$

Set F= Fshift, fundamental component shift to 0Hz.

B. Z-MUSIC

Music method is from the class of eigen decomposition methods for which the observed data can be represented by P complex sinusoids in white noise, as follows:

$$X(n) = \sum_{i=1}^{P} Ai\ e^{j(2\pi Fin + \vartheta i)} + e(n) \text{.... [12]}$$

The zooming technique is employed to reduce the computation time and to optimize the frequency component estimation. The proposed ZMUSIC algorithm is based on frequency shifting and decimating a discrete-time signal to determine the spectrum in a specific frequency bandwidth. In this paper, ZMUSIC is applied to detect the characteristic frequencies induced by bearing faults contained in the current [3].

Firstly, the discrete-time signal i(n) is obtained after sampling the signal i(t) at the frequency fs. The fundamental frequency f1 is evaluated by using the CZT to analyze the bandwidth. F1 is the ideal value of the fundamental frequency. Then the fundamental component of i(n) is turned to be DC by shifting it to 0Hz. Now the characteristic frequency which is $|f1 \pm mfv|$ earlier is change to just |mfv|.

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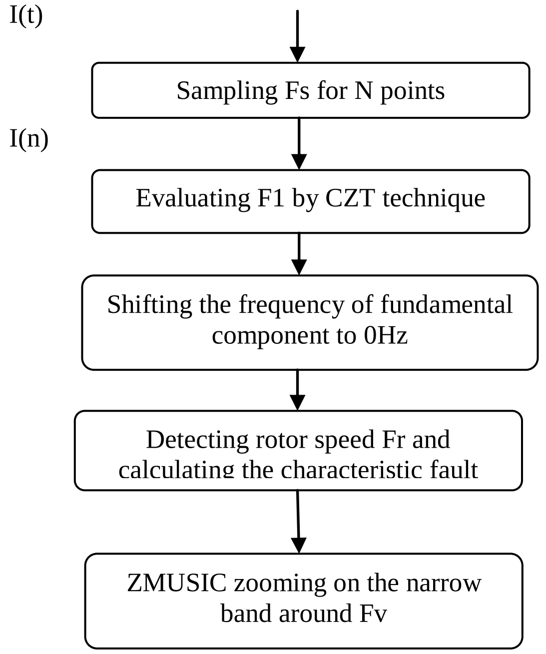

Figure 2: Flow Chart of CZT and ZMUSIC

C. MCM

Let us consider the case of a signal *xin*[*k*], sampled at*Fs*. In order to state its frequency *fin* in the range[*fa*, *fb*]a reference signal with the same sampling frequencyand a $x^i_{ref}[K]$ variable frequency *fi* ∈ [*fa*, *fb*] is chosen, so that the estimated frequency *fin* is the one corresponding to the maximum covariance function between *xin*and x^i_{ref} with zero lag. Specifically let us assume a pure sinusoidal tone with varying frequency:

$$x^i_{ref}[K] = A_i \sin(2\pi f_i k + \emptyset) \text{.......... [13]}$$

Where $f_{min} = f_a < f_i < f_b = f_{max}$ and $0 < \Phi < \pi$,

$T_s = 1/F_s$. In the following we will assume without losinggenerality $A_i = 1$, $\forall i$. The cross-correlation function is used:

$$corrcoef(a,b) = \frac{cov(a,b)}{\sqrt{cov(a,a)cov(b,b)}} \text{...... [14]}$$

Let us define:

$$C(i) = corrcoef(x_{in}, x^i_{ref}) \text{................ [15]}$$

The estimation *fin* of the frequency of *xin*is obtained computingthe maximum of the absolute value of the cross-correlationfunction varying the reference frequency *fi* and the phase ∅. The step of variation of *fi* is the effective resolution of the∅. The step of variation of *fi* is the effective resolution of the estimated signal frequency, thatis independent of the sampling frequency and of the acquisition period. The phase is varied among zero and π relying on the absolute value of cross-correlationfunction:

$$f_{in} = \{f_i \wedge \emptyset | abs[C(i)] = max\} \text{.......... [16]}$$

The method here detailed will be referred to as *Maximum Covariance Method for Frequency Tracking* (MCMFT).The computational cost of MCMFT is directly related to the step of spanning of the reference tone and to the width of the frequency range. However the effectiveness is quite good, and only a few tenth of periods of the signal are sufficient to track the target frequency. Therefore a real-time implementation is possible, fixing a suitable step and a small range of frequencies [4].

4. Implementation

With reference to recent papers, there is large scope for working in the area of frequency domain analysis for current signature analysis of line current or voltage of induction motor. A set up is to be developed for squirrel cage induction motor with bidirectional static switches. These switches will control the power flow in case faults. The following figure shows the set up of the experiment.

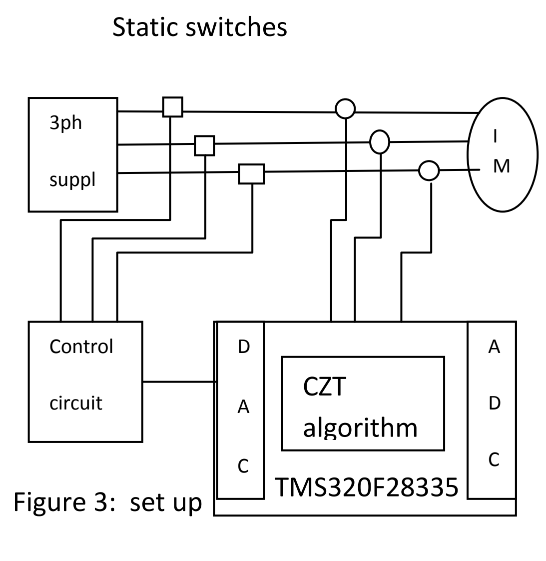

Figure 3: set up

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A 32 bit floating point digital signal controller TMS320F28335 with built in A/D and D/A converters[6] that are responsible for executing the CZT and ZMUSIC algorithm and initiating the trip signal respectively, is used for the online testing of the proposed algorithm. In addition, three static switches are used in series with 3 phase power supply in order to disconnect the motor from the supply in case of any fault or undesirable disturbance [8].

6. Conclusion

This paper focusses the fault diagnosis in induction motor. The frequency domain environment is discussed in detail. The mathematical implementation of the methods like ZMUSIC, CZT and MCM is shown for diagnosis. The implementation guidelines using a processor TMS320F28335 is demonstrated.

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