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Wavelet Decomposition based Skewness and Kurtosis Analysis for Assessment of Stator Current Harmonics in a PWM – Fed Induction Motor Drive during Single Phasing Condition

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Abstract

Induction motors are widely used as electrical drives in industrial application for their good efficiency and reliability in operation. This paper presents a fault detection method of a sinusoidal PWM inverter fed induction machine during single phasing. Stator current harmonics are analyzed by assessing kurtosis and skewness values of harmonic spectrums both at normal and at fault condition. The observation is based on a model designed through computer simulation. The mother wavelet used here is 'db4'. The fault condition leads to changes in the values of skewness and kurtosis which are very much optimistic to detect such fault condition in induction motor.

Key words

Discrete Wavelet Transform (DWT), kurtosis, skewness, single phasing.

1. Introduction

Induction motors are considered the main workhorse of the industry due to their ruggedness, versatility and low manufacturing cost. Although Induction motors are simple reliable machines, their annual failure rate is conservatively estimated at 3% per annum [1]. Thus, it has become an important aspect to make the induction motors failure proof to reduce the down time of the industries. For this purpose an early detection of motor faults is highly desirable by which any catastrophic damage or any potentially dangerous situation can be avoided. A lot of study has been done on the detection of these faults in induction motors where the motors have been mathematically modeled [2] and different analysis techniques like motor current signature analysis [3-4], Concordia analysis [5-6] and sequence components based assessment techniques have been introduced for fault assessment. PWM fed Induction motors which are extensively used in industries for their variable speed operation are more reliable than those supplied directly online. Fuzzy logic has been used to detect faults modes of PWM fed induction motors [7]. Fuzzy logic based systems, wavelet decomposition, PSD have been introduced for motor fault diagnosis [8] – [10] along with Park and Clarke domain where different features of motor current have been extracted to detect different faults in induction motor [11] – [16].

In this paper single phasing of a PWM fed induction motor has been considered. At normal condition a three phase induction motor is fed by a sinusoidal PWM inverter. The fault single phasing refers to loss of one of the three phases at the stator terminals. At this, condition negative sequence component generates along with positive sequence components and the resultant stator current increases. The negative sequence components have been assessed in [17]. The stator current at single phasing has also been assessed using feature pattern extraction method [17]. Radar, Concordia and FFT based many fault diagnosis methods have been introduced [18] – [20]. However, very little work has been done to use Kurtosis band Skewness in fault diagnosis. This limitation has motivated this work.

In this paper, the stator current drawn by the induction motor from PWM inverter has been analyzed by harmonics assessment using wavelet decomposition based technique. A stator current measurement unit has been used to extract the current signal from the healthy phases and Wavelet Transform algorithm is used to find the kurtosis and skewness values of the approximate and detail coefficients which are compared for normal and faulty (unbalanced) conditions to detect the single phasing.

2. Wavelet Transform

The frequency information of stationary and periodic waveform is produced by Fourier Transform (FT). But it is not appropriate for a signal that has transitory characteristics such as drifts, abrupt changes, and frequency trends. FT gives no information on the time instant at which a particular frequency exists and only tells whether the frequency component exists or not. Hence, FT is unsuitable for non-stationary signals. To overcome this problem, the Fourier Transform has been adapted to analyze small sections of the signal at a time. This technique is known as short-time Fourier transform (STFT), or windowing technique but its main drawback is that only band of frequencies available at certain time intervals. Consequently, resolution problem and problem with the size of window function arises. The wavelet transform was then introduced with the idea of overcoming these difficulties mentioned above. A windowing technique with variable-size region is then used to perform the signal analysis, which can be the stator current, the case that is considered here. Wavelet analysis allows the use of long time intervals where we want more precise low-frequency information, and shorter regions where we want high-frequency information. In this paper 'db4' is considered as the mother wavelet.

3. Skewness and Kurtosis

To detect the single phasing condition two statistical parameters skewness and kurtosis are used here [21]. Skewness can be mathematically defined as the averaged cubed deviation from the mean divided by the standard deviation cubed. It is said to be positively skewed if the result of the computation is greater than zero. If the computational result less than zero, it is negatively skewed and equal to zero means it is symmetric. For univariate data Y_1, Y_2, ..., Y_N, the formula for skewness is:

$$\mathbf{Skewness} = \frac{\sum_{i=1}^{N}(Y_i - \bar{Y})^3 / N}{S^3}$$

Where, **Y bar** is the mean, **S** is the standard deviation, and **N** is the number of data points. Skewness indicator used in distribution analysis as a sign of asymmetry and deviation from a normal distribution.

Interpretation:

a) Skewness > 0 - Right skewed distribution - most values are concentrated on left of the mean, with extreme values to the right.

b) Skewness < 0 - Left skewed distribution - most values are concentrated on the right of the mean, with extreme values to the left.

c) Skewness = 0 - mean = median, the distribution is symmetrical around the mean.

Peakedness or flatness of data can be measured by measurement of kurtosis from a given data sets. That is, data sets with high kurtosis tend to have a distinct peak near the mean, decline rather rapidly, and have heavy tails. Data sets with low kurtosis tend to have a flat top near the mean rather than a sharp peak. A uniform distribution would be the extreme case.

For univariate data $Y_1, Y_2, ..., Y_N$, the formula for kurtosis is:

$$\mathbf{Kurtosis} = \frac{\sum_{i=1}^{N}(Y_i - \bar{Y})^4 / N}{S^4} \qquad (1)$$

Where, **Y bar** is the mean, **S** is the standard deviation, and **N** is the number of data points. Kurtosis [21] indicator used in distribution analysis as a sign of flattening or "peakedness" of a distribution.

Interpretation:

a) Kurtosis > 3 - Leptokurtic distribution, sharper than a normal distribution, with values concentrated around the mean and thicker tails. This means high probability for extreme values.

b) Kurtosis < 3 - Platykurtic distribution, flatter than a normal distribution with a wider peak. The probability for extreme values is less than for a normal distribution, and the values are wider spread around the mean.

c) Kurtosis = 3 - Mesokurtic distribution - normal distribution for example.

3. Computer Modeling

The total analysis has been done by computer simulation using MATLAB [22]. Here a 3ph Induction Motor of rating 3HP, 220V, 1725rpm is used, which is fed by a sinusoidal PWM inverter. The inverter uses a sinusoidal reference signal of 60Hz and a triangular wave of frequency 1980Hz. The output is fed to relays which produces the 3ph of sinusoidal voltage displaced by 120^0 apart. Its output is then fed to the stator of the Induction Motor, through Controlled Voltage Source. So, three phase balanced power is fed to the motor as shown in Fig. 1. The rotor of the motor is short-circuited and its stator leakage inductance is set to twice its normal. The load torque is set to its nominal value of 11.9 N-m. Here in order to create a single phase fault condition, Phase A was open circuited through a circuit breaker after some time of motor starting and its effect on the other phases B & C was studied by connecting a current measurement unit. The current signature obtained from phase B and phase C was analyzed separately for normal and fault condition with the help of Discrete Wavelet Transform (DWT). The Skewness and Kurtosis values are calculated in both the conditions for the approximate and detail coefficients in each and every decomposition level (upto 9th level) to detect single phasing fault.

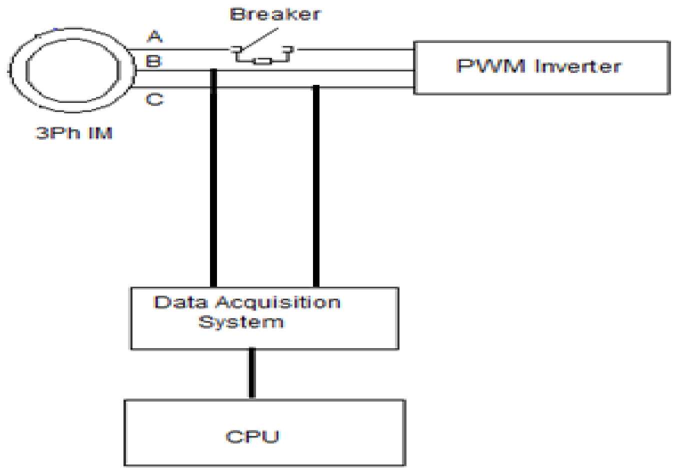

Fig.1. Experimental Model for Assessment of Single Phasing of a PWM Fed Induction Motor

4. Stator Current Analysis

Current through phase A becomes zero in case of single phasing condition but currents through other healthy phase B and C increases. Healthy phases' currents are captured and then assessed using Discrete Wavelet Transform (DWT). Here, well-known Daubechies wavelet 'db4' (properties: asymmetric and orthogonal) has been used as mother wavelet, where db4 scaling functions are as follows:

$$\alpha_1 = \frac{1+\sqrt{3}}{4\sqrt{2}}, \quad \alpha_2 = \frac{3+\sqrt{3}}{4\sqrt{2}}$$
$$\alpha_3 = \frac{3-\sqrt{3}}{4\sqrt{2}}, \quad \alpha_4 = \frac{1-\sqrt{3}}{4\sqrt{2}} \tag{2}$$

and wavelets are as follows:

$$\beta_1 = \frac{1-\sqrt{3}}{4\sqrt{2}}, \quad \beta_2 = \frac{\sqrt{3}-3}{4\sqrt{2}}$$
$$\beta_3 = \frac{3+\sqrt{3}}{4\sqrt{2}}, \quad \beta_4 = \frac{-1-\sqrt{3}}{4\sqrt{2}} \tag{3}$$

Healthy phase currents are decomposed at different DWT levels and at each level, the skewness and kurtosis values of harmonics spectrum are assessed by measuring skewness and kurtosis values. The wavelet decomposition based result obtained corresponding to healthy phases B and C (for normal and faulty condition) is shown graphically in Fig. 2, 3, 4, 5, 6, 7, 8, and 9. Dashed line corresponds to single phasing condition (fault or unbalanced condition) and solid continuous line corresponds to normal condition for all the mentioned figures.

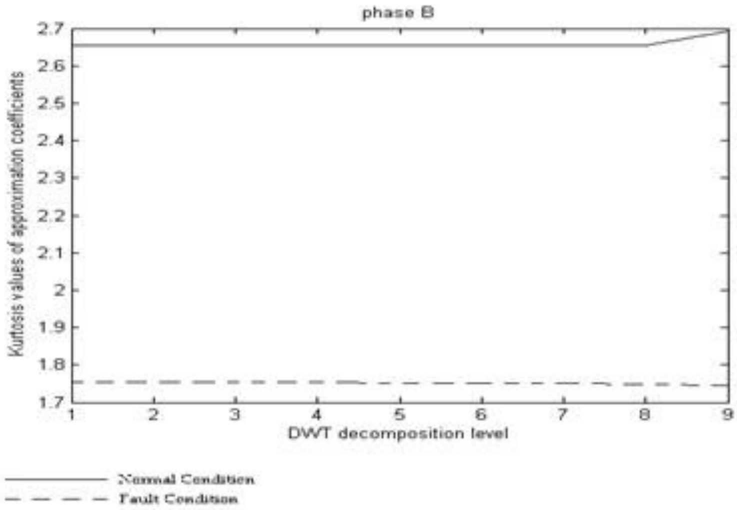

Fig.2. Kurtosis Values of Approximate Coefficients for Phase B Current Plotted with Respect to DWT Decomposition Level

In Fig.2, Kurtosis values of approximate coefficients for B Phase Current are plotted with respect to DWT decomposition levels. It shows almost constant value both at normal and fault condition.

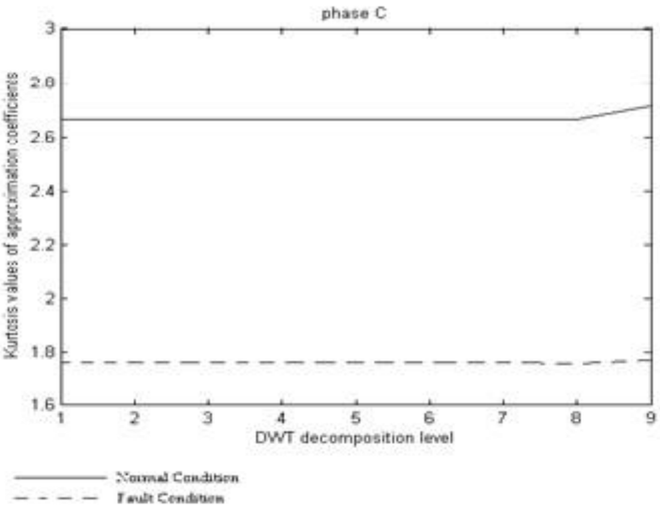

Fig.3. Kurtosis Values of Approximate Coefficients for Phase C Current Plotted with Respect to DWT Decomposition Level

In Fig.3, Kurtosis values of approximate coefficients for C Phase Current are plotted with respect to DWT decomposition levels. It shows almost constant value both at normal and fault condition.

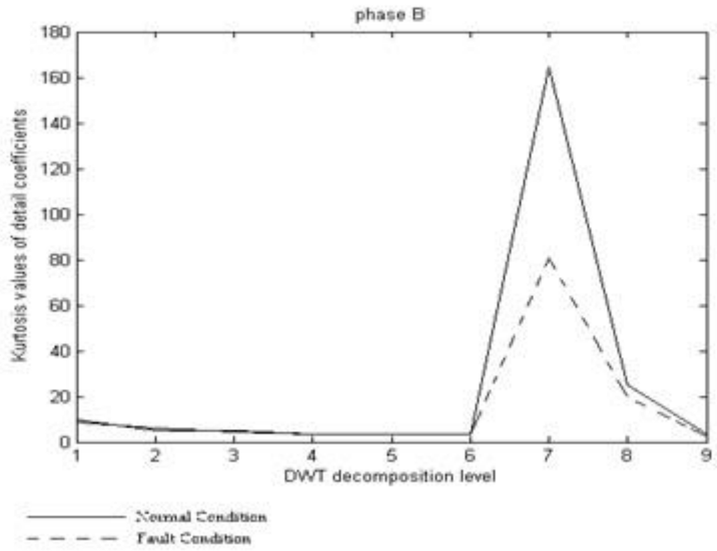

Fig.4. Kurtosis Values of Detail Coefficients for Phase B Current Plotted with Respect to DWT Decomposition Level

In Fig.4, Kurtosis values of detail coefficients for B Phase Current are plotted with respect to DWT decomposition levels. It shows almost constant value up to level 6, maximum at level 7 and then negative slope for both normal and fault condition.

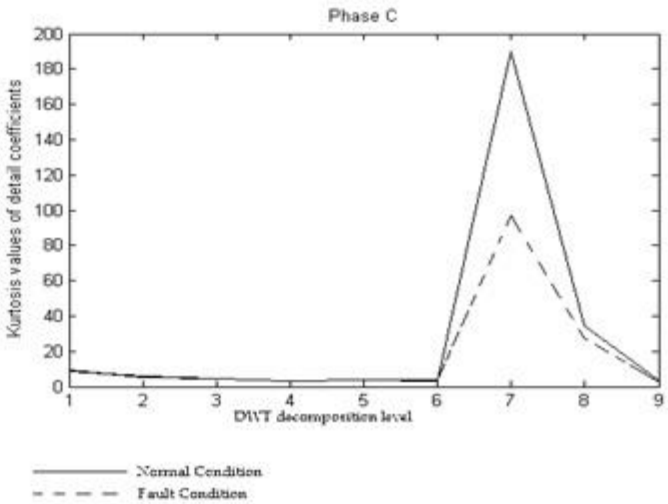

Fig.5. Kurtosis Values of Detail Coefficients for Phase C Current Plotted with Respect to DWT Decomposition Level

In Fig.5, Kurtosis values of detail coefficients for C Phase Current are plotted with respect to DWT decomposition levels. It shows almost constant value up to level 6, maximum at level 7 and then negative slope for both normal and fault condition.

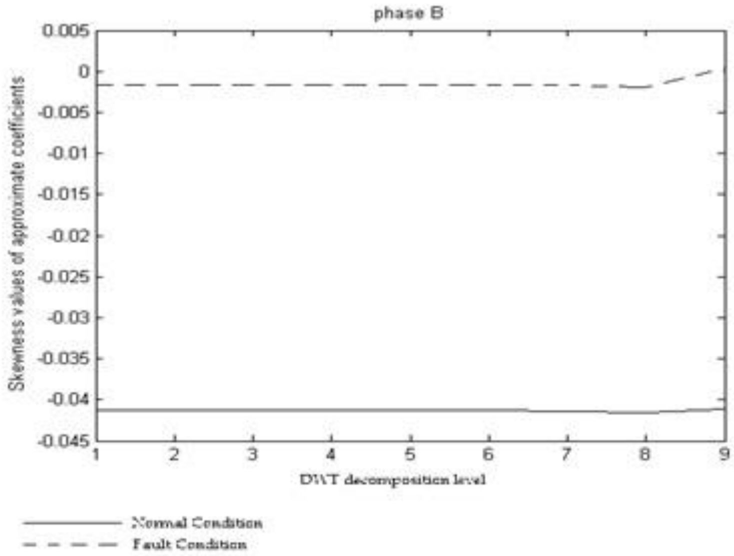

Fig.6. Skewness Values of Approximate Coefficients for Phase B Current Plotted with Respect to DWT Decomposition Level

In Fig.6, Skewness values of approximate coefficients for B Phase Current are plotted with respect to DWT decomposition levels. It shows almost constant value both at normal and fault condition.

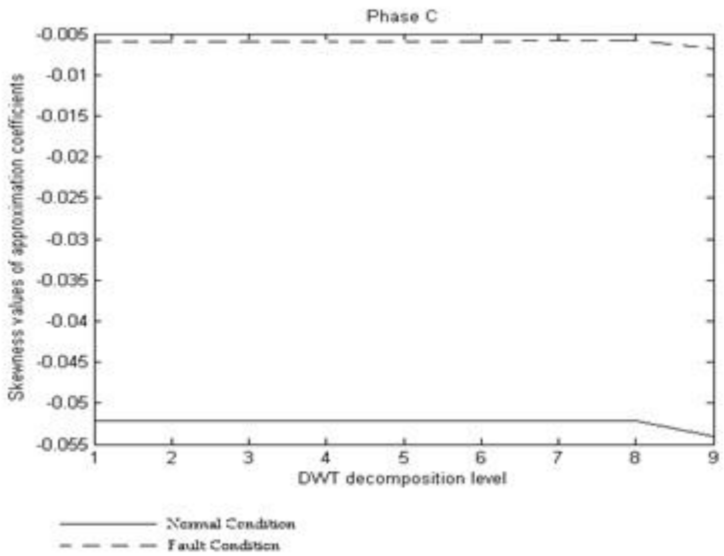

Fig.7. Skewness Values of Approximate Coefficients for Phase C Current Plotted with Respect to DWT Decomposition Level

In Fig.7, Skewness values of approximate coefficients for C Phase Current are plotted with respect to DWT decomposition levels. It shows almost constant value both at normal and fault condition.

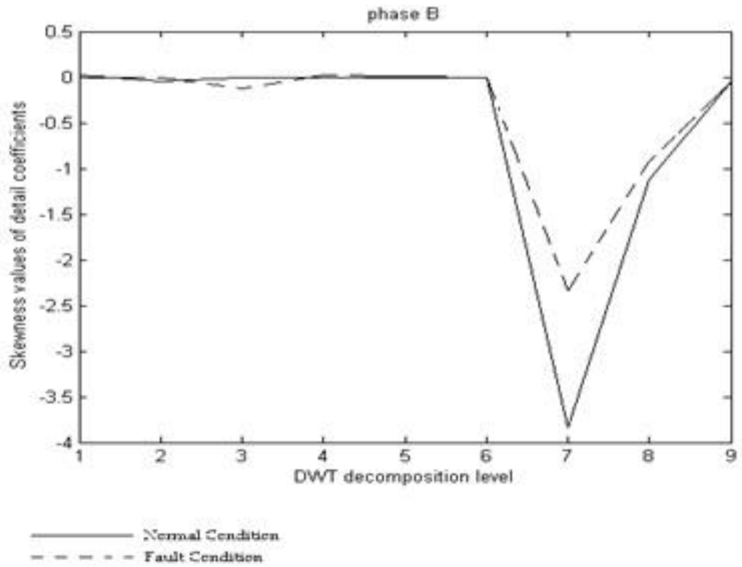

Fig.8. Skewness Values of Detail Coefficients for Phase B Current Plotted with Respect to DWT Decomposition Level

In Fig.8, Skewness values of detail coefficients for B Phase Current are plotted with respect to DWT decomposition levels. It shows almost constant value up to level 6, minimum at level 7 and then positive slope for both normal and fault condition.

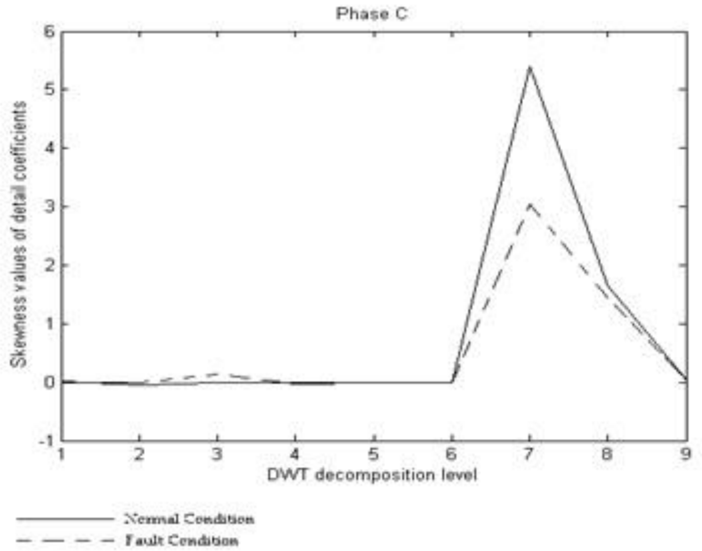

Fig.9. Skewness Values of Detail Coefficients for Phase C Current Plotted with Respect to DWT Decomposition Level

In Fig.9, Skewness values of detail coefficients for C Phase Current are plotted with respect to DWT decomposition levels. It shows almost constant value up to level 6, maximum at level 7 and then positive slope for both normal and fault condition.

5. Observation

In this paper single phasing have been done in phase A and current signature is captured from phase B and phase C. Discrete Wavelet Transform ('db4' is taken as a mother wavelet) is used to decomposed phase B and C current and skewness and kurtosis values have been calculated for detail and approximate coefficients for both the conditions to detect the faulty condition.

The kurtosis values of approximate coefficients for phase B and phase C during the normal and fault condition have been plotted in Fig. 2 and Fig. 3 respectively. There is a clear difference between these two plots, which clearly suggests the faulty condition.

Fig. 6 and Fig. 7 depict the skewness values of approximate coefficients in both the conditions (normal and fault) for phase B and C current respectively. In these two plots clearly there is a difference between normal and fault condition.

Fig. 4 and Fig. 5 are used for comparison of Kurtosis values of detail coefficients for phase B and C current in normal and fault conditions respectively. In these figures the differences arise from DWT decomposition level 6 and maximum difference are observed in DWT decomposition level 7. Fig. 8 depicts the skewness values of detail coefficients for phase-B current in normal and faulty conditions, where the differences between the two plots are started at DWT decomposition level 6 and it is minimum at DWT decomposition level 7. In Fig. 9 the Skewness values of detail coefficients for phase-C current have been plotted in normal and faulty conditions where the difference is maximum at DWT decomposition level 7 which clearly suggests the single phasing condition in PWM fed induction motor.

6. Single Phasing Detection Algorithm

An algorithm for single phasing or fault detection has been also made as follows:

a. Step down the stator currents through current transformer

b. Sample them at proper sampling frequency

c. Capture the sampled values through data acquisition system

d. If the value of captured signal is zero, then faulty condition can be assessed, otherwise

e. Apply discrete wavelet transform technique on the captured signal

f. Determine skewness and kurtosis values of approximate and detail coefficients from DWT decomposition levels (upto 9^{th} level)

g. Compare all above values from standard or normal condition measured values

h. Diagnose the single phasing or faulty condition based on measurement and comparison of above parameters values in two conditions.

7. Conclusion

In this paper skewness and kurtosis values of approximate and detail coefficients of harmonic spectrums have been measured in normal and faulty condition to detect the single phasing condition of a PWM fed induction motor. Though single phasing was occurred in phase A and DWT have been done for healthy phases (B and C) current and all the parameters have been calculated thereafter. The observation shows clear difference of those parameters at faulty condition from normal condition. This indicates that continuous measurement, monitoring and comparison can be done for diagnosis of fault like single phasing. Another clear observation can be noted that when single phasing occurs in phase A, its effect falls on phase B and phase C significantly. The kurtosis value of approximate coefficients decreases and skewness value of approximate coefficients increases many folds in case of fault condition which can be easily noted from the above depicted figures.

References

1. T.C. Akuner, H. Calik, “Analysis of balanced three phase induction motor performance under unbalanced supply using simulation and experimental results”, *Electronics and Electrical Engineering, Elektronika IR Electrotechnika,* ISSN-1392-1215, no.3(109), pp. 41-45, 2011.
2. J.H. Jung, J.J. Lee and B.H. Kwon, “Online diagnosis of induction motors using MCSA”, *IEEE Transactions on Industrial Electronics,* vol. 53, no. 6, pp. 1842–1852, December 2006.

3. Systems Applications, Engineering and Development vol 1, issue 1, pp. 13 – 17, 2007.
4. D.G. Dorrel, W.T. Thomson and S. Roach, “Analysis of airgap flux, current and vibration signals as a function of the combination of static and dynamic airgap eccentricity in 3-phase Induction motors”, *IEEE Trans. on Industr. Applications*, vol. 33, pp. 24 – 34, 1997.
5. F. Zidani, M.E.H. Benbouzid, D. Diallo, and Md.S.N. Saïd, “Induction motor stator faults diagnosis by a current concordia pattern-based fuzzy decision system”, *IEEE Transaction on Energy Conversion*, vol. 18, no. 4, pp. 469 – 475, December 2003.
6. D. Diallo, M.E.H. Benbouzid, D.Hamad, and X. Pierre, “Fault detection and diagnosis in an induction machine drive: a pattern recognition approach based on concordia stator mean current vector”, *IEEE Transaction on Energy Conversion,* vol. 20, no. 3, pp. 512 – 519, September 2005.
7. M.E.H. Benbouzid, “A review of induction motor signature analysis as a medium for fault detection”, *IEEE Trans Ind. Electron.,* vol. 47, issue 5, pp. 984 – 993, 2000.
8. F. Zidani, D. Diallo, M.E.H. Benbouzid, R.N. Saïd, “A Fuzzy-based approach for the diagnosis of fault modes in a voltage-fed PWM inverter induction motor drive”, *IEEE Transactions On Industrial Electronics,* vol. 55, no. 2, February 2008.
9. J. Cusido, L. Romeral, J. A. Ortego, J. A. Rosero and A. G. Espinosa, “Fault detection in induction machines using power spectral density in Wavelet decomposition”, *IEEE Transactions on Industrial Electronics,* vol. 55, no. 2, pp. 633 – 643, February, 2008.
10. J. Cusido, A. Jornet, L. Romeral, J. A. Ortega and A. Garcia, “Wavelet and PSD as a fault detection technique”, *ITMC 2006-Instrumentation and Measurement Technology Conference, proceeding of IEEE,* Sorrento, Italy, pp. 1397 – 1400, 24-27 April, 2006.
11. M. E. H. Benbouzid et al, “Monitoring and diagnosis of Induction motor electrical faults using a current Park's vector pattern approach”, *Proc. of IEEE Int. Conf. On Electrical Machines and Drives,* Seattle, WA, pp. 275 – 277, 1999.

12. H. Nejjariet al., "Monitoring and diagnosis of induction motors electrical faults using a current Park's vector pattern learning approach", *IEEE Trans. Ind. Appl.,* vol. 36, no. 3, pp. 730 – 735, May/Jun. 2000.
13. S. Chattopadhyay, M. Mitra, and S. Sengupta: "Harmonic Analysis in a Three-Phase System using Park Transformation Technique", International Journal on Modeling, Measurement and Control of General Physics and Electrical Applications, AMSE, Series –A, vol. 80, N^{o}–3, Modeling-A, pp. 42-58, 2007.
14. S. Chattopadhyay, M. Mitra, and S. Sengupta: "Electric Power Quality", Springer, 2010, first edition, ISBN: 978-94-007-0634-7.
15. S. Chattopadhyay, S. Karmakar, M. Mitra, S. Sengupta.: 'Assessment of crawling of an induction motor by stator current Concordia analysis', *Electron. Lett.,* vol. 48, Issue 14, pp. 841–842, 5th July 2012.
16. S. Chattopadhyay, M. Mitra, S. Sengupta,"Area based approach in power quality assessment", *International Journal of Power Management Electronics,* ID-147359, Pages-6, ISSN: 16876679, May 2008.
17. S. Chattopadhyay, S. Karmakar, M. Mitra, S. Sengupta, "Symmetrical components and current Concordia based assessment of single phasing of an induction motor by feature pattern extraction method and Radar analysis", *International Journal of Electrical Power and Energy Systems (Elsevier),* vol. 37, Issue 1, pp. 43 – 49, May 2012.
18. S Chattopadhyay, S Karmakar, M Mitra, S Sengupta, Radar Analysis of Stator Current Concordia for Diagnosis of Unbalance in Mass and Cracks in rotor bar of an Squirrel Cage Induction Motor, International Journal on Modeling, Measurement and Control of General Physics and Electrical Applications, AMSE, Series -A, vol. – 85, issue – 1, pp – 50-61, 2012. ISSN: 1259-5985.
19. S Chattopadhyay, S Karmakar, M Mitra, S Sengupta, Loss of phase fault detection of an induction motor, International Journal on Modeling, Measurement and Control of General Physics and Electrical Applications, AMSE, Series -A, vol. – 85, issue – 2, pp – 18-34, 2011, ISSN: 1259-5985.
20. S Chattopadhyay, M Mitra, S Sengupta, Part wise linear characteristics of FFT based spectrum of Current Transformer, International Journal on Modeling, Measurement and Control of General Physics and Electrical Applications, AMSE, Series -A, Vol. 84, Issue 1, 2011, pp 89-98, ISSN: 1259-5985.

21. "Engineering Statistics Handbook", NIST/SEMATECH e-Handbook of Statistical Methods, NIST, Retrieved 18th March 2012.
22. MATLAB® 7.7 (MATLAB demos).