

EARLY, DIAGNOSIS OF AIRGAP ECCENTRICITY FAULT IN THE INVERTER DRIVEN INDUCTION MOTOR DRIVES BY WAVELET TRANSFORM

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Abstract: *In the present time, the inverter-driven induction motors drives are being widely employed in the industries for variable speed applications. These drives are replacing D.C. motors and thyristor bridges day by day in the industries. In the past, the Fast Fourier Transform (FFT) algorithm has been successfully implemented for the diagnosis of air-gap fault in the induction motor. This algorithm used to diagnose various induction motor faults in the steady state conditions for constant load. However, the FFT algorithm unable to diagnose induction motor faults in the transient condition. Therefore, early fault detection is not possible by this method. This research paper proposed a wavelet transform based new technique for early diagnosis of air-gap fault in the induction motor. By using this technique, the airgap fault may be diagnosed in the transient condition and fault may be averted before become more catastrophic. Therefore, early diagnosis of airgap fault is possible by this method. As a result, industries may save large revenues and unexpected failure condition. In this research paper, an inverter-driven induction motor setup has been proposed and diagnosed air-gap eccentricity fault in the transient condition by time-domain and time-frequency domain(wavelet transform) techniques. The Motor Current Signature Analysis(MCSA) technique has been used for healthy and faulty conditions of the motor. The low frequency approximation signal has been used to distinguish healthy and faulty induction motor.*

Key words: *Pulse Width Modulated Inverter (PWM), Induction Motor, Airgap Fault Detection and Identification, MCSA, Time-Domain Analysis, Wavelet Transform.*

1. Introduction

Nowadays, the three-phase squirrel cage induction motors are omnipresent in industrial and manufacturing processes. This is mainly due to their low cost, ruggedness, reasonable size and ease of control. Commonly, the induction motors work under many stresses from various natures (electric,

thermal, mechanical and environment) which may affect their lifespan by involving the occurrence of stator and/or rotor faults leading to unscheduled downtime. Therefore, one may significantly reduce the maintenance costs by preventing sudden failures in induction motor. This is the main aim of the operator of electrical drives[1,3,7,10].

The rotating electrical machines play a most important role in the world's industrial life. In power utilities and petrochemical, the failure of electrical motors causes a high cost. It is due to the loss of production, high emergency maintenance costs and lost revenues. The industries response towards this predicament of unexpected interruptions of work is by using "catch it before it fails" approach. The oldest technique for preventive maintenance was tearing the electrical machine down and then looking at it closely. However, taking the motor out of service is costly and time consuming. This is why today's modern industry management is more interested than ever before in adopting new health monitoring techniques, on-line or off-line, to assess and evaluate the rotating electrical machine's performance condition[1,5-6].

Most of the faults in three-phase induction motors have relationship with air-gap eccentricity which is the condition of the unequal air-gap between the stator and the rotor. This fault can result from variety of sources such as incorrect bearing positioning during assembly, worn bearings, a shaft deflection, heavy load and so on. In general, there are two forms of air-gap eccentricity: radial (where the axis of the rotor is parallel to the stator axis) and axial. Each of them can be static (where the rotor is displaced from the stator bore centre but is still turning upon its own axis) or dynamic eccentricity (where the rotor is still turning upon the stator bore centre but not on its own centre)[2,8,11].

There are different research works in the field of

induction machine fault diagnosis include electrical, mechanical and magnetic techniques. These techniques can be regarded as basis for developing on-line and/or off-line rotating electrical machine health monitoring systems. The electrical and magnetic techniques include magnetic flux measurement, stator current analysis, rotor current analysis, partial discharges for evaluating stator insulation strength for high voltage motors, shaft-induced voltages, etc. The mechanical techniques include the machine bearing vibration-monitoring systems, speed fluctuation analysis of induction machines and bearing temperature measurement. The MCSA for incipient fault detection has received much attention in recent years. For most purposes current monitoring can be implemented inexpensively on any size of machine [2,4,6,10,13,16].

The induction machine modelling has continuously attracted with the attention of researchers not only because such machines are made and used in largest number of applications but also due to their varied modes of operation both under steady state and dynamic states[1,4]. In electric drive system elements, such machines is a part of the control system elements, which is to be controlled by the dynamic behavior of Induction Motor (IM) then the dynamic model of induction motor has to be considered. The dynamic model considers the instantaneous effects of varying voltage/currents, stator frequency and torque disturbance [1,5,10].

The use of signature analysis of complex apparent power modulus as a new technique for the diagnostics of mixed airgap-eccentricity condition in operating three-phase squirrel-cage induction motors reported in[2].

A new automated approach for testing inverter-fed induction machines for airgap eccentricity has been reported in[3]. Hyun, D. et. al. used the concept to use the inverter to excite the machine with a pulsating field at multiple angular positions to observe the variation of equivalent impedance due to eccentricity, whenever the motor is stopped. The leakage inductance under standstill condition is used as an indicator for increasing airgap.

The comprehensive review of the induction motor faults and its diagnosis techniques has been reported in [4]. Siddiqui, K.M. et. al. have concluded that the fault diagnosis in the inverter driven motors are difficult because inverter produces noise but the advanced digital signal processing based

transformative techniques may be the better solution for the early fault detection purpose.

A new method has been reported in[5] to detect fault conditions in inverter fed AC machines caused by asymmetries in the airgap. Wolbank, T.M. et. al. used a special observer structure for diagnosing of airgap irregularity.

The rotor broken bar fault has been diagnosed in the steady state and transient conditions for the inverter driven squirrel cage induction motor. Siddiqui, K.M. et.al., have reported in[6] that the FFT algorithm unable to diagnose rotor broken bar fault for no-load condition. Therefore, authors have overcome this problem and diagnosed the rotor broken bar fault in the transient condition for all load by low frequency approximation signal.

Trabelsi, M. et.al. reported a new approach in[7] for single and multiple open-circuit fault diagnosis purpose in voltage source inverter fed induction motors. The diagnosis procedure is based on the knowledge of the outputs inverter currents distribution in α - β frame combined with additional diagnosis variables which use their mean values.

Hong, J. et.al. reported in[8], a new inverter-embedded test approach for detecting eccentricity for induction motors. Authors used the main concept to use the inverter to perform a standstill test whenever the motor is stopped, to extract information on motor eccentricity. The motor is excited with a low frequency pulsating AC field superimposed on different levels of DC fields, and the variation in the differential inductance pattern due to the change in the degree of magnetic saturation caused by eccentricity.

Schoen, R. et. al. in[9] proposed a new method for induction motor fault detection purpose by built on line system utilizes artificial neural networks to learn the spectral characteristics of a good motor operating on-line.

Siddiqui, K.M. et.al. in [10] have developed a simulation model and diagnosed bearing fault in the transient condition by time domain analysis. Authors have used many motor signatures for differentiating the healthy and faulty conditions of the bearing.

Huang, X. et.al. in[11] proposed a scheme to monitor voltage and current space vectors simultaneously in order to monitor the level of air-gap eccentricity in an induction motor. An artificial neural network is used to learn the complicated relationship and estimate corresponding signature amplitudes over a wide range of operating conditions.

Filippetti, F. et.al. in [12] has presented an

induction machine rotor fault diagnosis based on a neural network approach, after the neural network was trained using data achieved through experimental tests on healthy machines and through simulation in case of faulted machines, the diagnostic system was found able to distinguish between healthy and faulty machines.

Nandi, S. et.al. in [13] has proposed the detection of air-gap eccentricity in induction machines by measuring the harmonic content in the machine line currents. However, authors proposed a new way for modeling the machine under eccentricity. The winding function approach accounting for all the space harmonics in the machine was used to calculate all the mutual and magnetizing inductance's for the induction machine with eccentric rotors between healthy and faulty machines.

In reality both static and dynamic eccentricities tend to co-exist. An inherent level of static eccentricity exists even in newly manufactured machines due to manufacturing and assembly method, as has been reported by Dorrell, D.G. et. al. in[14]. This causes a steady unbalanced magnetic pull (UMP) in one direction. With usage, this may lead to bent rotor shaft, bearing wear and tear etc. This might result in some degree of dynamic eccentricity. Unless detected early, these effects may snowball into stator to rotor hub causing a major breakdown of the machine [15,19].

In the past, many researchers used various techniques for diagnosing airgap eccentricity fault of the induction motor. But, authors have not diagnosed airgap eccentricity fault in the transient condition, if any fault having very small frequency. Therefore, in this present paper, we are making an attempt to solve the problem by a proposed setup. We have used wavelet transform's approximation stator current signal for airgap eccentricity fault diagnosis purpose. This new technique may give accurate information of the airgap eccentricity faulty conditions at any stage.

2. Proposed Inverter Driven Squirrel Cage Induction Motor Setup

A three-phase squirrel induction motor having rating of 3 HP, 220 V, 1430 RPM is fed by a PWM inverter has been used for analysis purpose. The simulation model has been formed in the form of block diagram is as shown in Fig.1. The simulation has been done in the latest MATLAB/Simulink environment. The constant rated load torque has been applied i.e. 15 N.m. The current transducer used to sense stator current which is pre-installed

with motor. The anti-aliasing filter has been used to avoid aliasing. The analog-to-digital converter has been used to convert analog signal into the digital signal. That digital signal has been used to distinguish healthy and airgap eccentricity faulty conditions. There are two techniques have been used in this paper; time domain and time-frequency domain(wavelet transform).

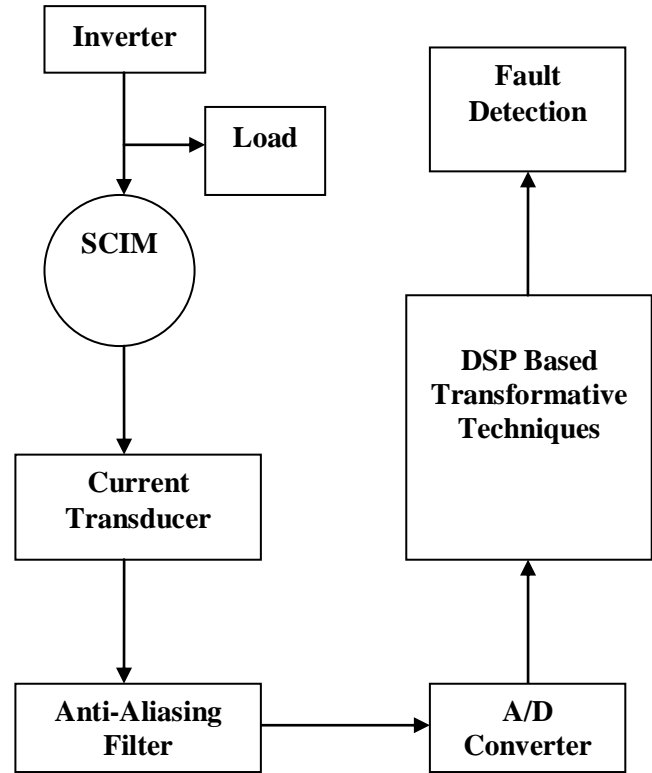


Fig. 1. Proposed Experimental Setup of Inverter Driven Induction Motor Drives

3. Time Domain Analysis

In this section, the induction motor healthy and airgap eccentricity faulty conditions analysis has been done. The mathematical modelling of the induction motor healthy and faulty conditions has been given in[1,10].

3.1 Healthy Condition Analysis of the Induction Motor

The simulation results in healthy motor condition of the induction motor are as shown in Fig.2. Total four motor parameters have been considered for the analysis of the squirrel cage induction motor. These parameters are stator current, rotor current, rotor speed and electromagnetic torque. Two healthy modes have been considered; First healthy mode is for standstill condition and second is for running condition. Since, our focus is towards the transient

analysis of the motor. Therefore, it is also essential to observe that how motor is behaving in the running conditions. Firstly, for healthy mode of the induction motor, the slip is set at 1($s=1$) with nominal mechanical load torque 15 N-m. Secondly, for running condition the slip is set at 0.04 with same load torque. The changes in motor parameters may be observed in Table. 1 for both healthy and airgap eccentricity faulty conditions of the motor. This table clearly reveals the changes in motor parameters in transient conditions for healthy as well as for airgap eccentricity faulty conditions.

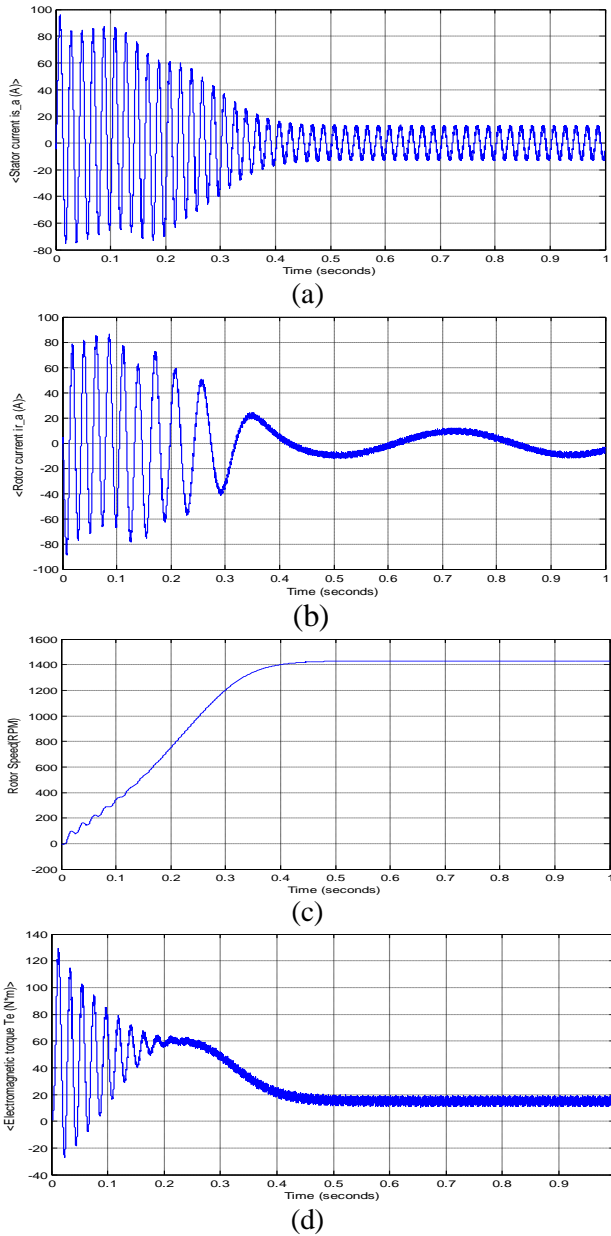


Fig. 2. Healthy Condition of the Motor (a) Stator Current, (b) Rotor Current, (c) Rotor Speed, (d) Electromagnetic Torque

The obtained results in the Fig. 2 show that all four considered motor parameters have been reached in the steady state condition after 0.4 seconds. If we change the motor parameters used in the proposed model such as slip and load torque then the healthy induction motor treated like as airgap eccentricity faulty condition. If we change load torque above the prescribed limit of the motor then the airgap between the stator and rotor will be un-equal. Consequently, the unbalanced radial forces (unbalanced magnetic pull or UMP) may cause rotor to rub with stator. If further increases load torque with corresponding slip then the airgap eccentricity becomes large. If, this airgap eccentricity faulty condition not diagnosed on time, drastic consequences will be taken place in the whole industrial plant. The simulation model has been run only for 1 sec for clear revelation of the transient characteristics of the motor. Since, this is a non-intrusive technique; therefore obtained results for healthy as well as for airgap eccentricity faulty conditions of the motor should be different. As a result, an effective airgap eccentricity faulty condition diagnosis would be carried out.

3.2 Airgap Eccentricity Faulty Condition Analysis of the Induction Motor

The healthy squirrel cage induction motor has been treated as the airgap eccentricity faulty condition in the proposed model. If varying some motor parameters such as load torque as well as corresponding slip. In this section, the airgap eccentricity fault analysis of the induction motor has been carried out in time domain. The 20 %, 30% and 40% airgap irregularity analysis has been done. The change in motor parameters of both healthy and all airgap eccentricity faulty conditions may be observed in the Table. 1. The results obtained for 20% airgap eccentricity faulty condition is as shown in Fig.3.

The obtained results for 20% airgap eccentricity faulty condition have been compared with the results of healthy condition which are shown in Fig.2 and Fig.3. After observing waveforms, it may be concluded that the obtained results are different. Because, it is a non-intrusive technique of fault diagnosis; therefore, we may say that efficient airgap eccentricity fault detection has been done by the time domain analysis.

From Fig.3 (a to d), it may be clearly observed that the transient state of the motor has been completely disturbed and correspondingly changes in motor parameters are as shown in Table. 1 for healthy as

well as airgap eccentricity faulty conditions.

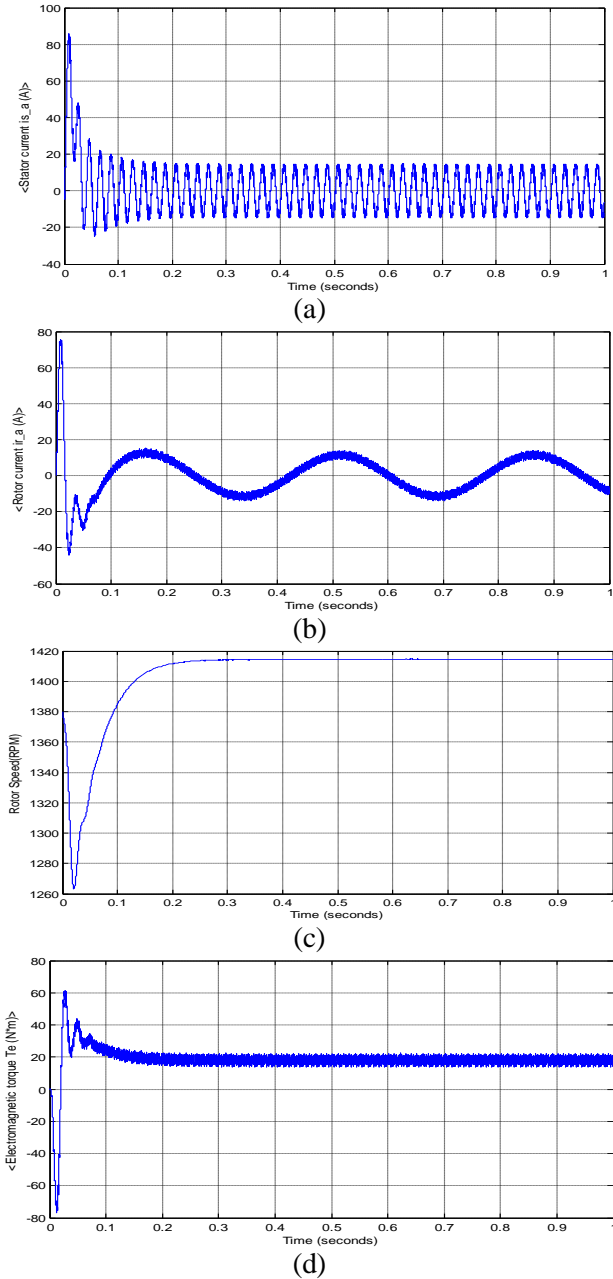


Fig. 3. Airgap Eccentricity (20%) Faulty Condition of the Motor (a) Stator Current, (b) Rotor Current, (c) Rotor Speed, (d) Electromagnetic Torque

From Table.1, it has been observed that the slip for both healthy conditions has been set 1 and 0.04 for standstill and running conditions respectively. The transient analysis has been done by first maximum transient peak of the motor parameters. The first maximum transient peak has been observed for both healthy and airgap eccentricity faulty conditions of the motor. The airgap between stator and rotor has been set 0 that means motor working with rated airgap eccentricity for both healthy conditions. In the standstill condition, the slip is set at 1

consequently speed of the Rotating Magnetic Field(RMF) reached in the steady state condition after 0.4 sec up to 1430 RPM. In this case, the rotor speed observed zero as shown in Fig.2(c). In the running condition of the motor, the slip is set as 0.04 consequently speed of rotor reached in the steady state condition after 0.4 sec upto 1430 RPM as shown in the Table. 1. It is the rated speed of the used induction motor. This condition has been achieved when there is not uneven airgap between stator and rotor. The airgap eccentricity fault analysis has been done for 20%,30% and 40% airgap eccentricity is as shown in Table.1.

Table. 1
Motor Parameters Variation for the Healthy and Airgap Eccentricity Faulty Conditions

MC	AGV (%)	Slip	MPTR C (A)	MPTS C (A)	RS (RPM)	MPTE MT (N-m)
HSC	0	1	86.17	95.66	1430	129.26
HRC	0	0.04	79.80	86.76	1430	54.32
FAGC	20	0.08	75.65	85.59	1414	61.38
FAGC	30	0.08	75.58	85.57	1407	61.72
FAGC	40	0.08	75.51	85.55	1399	62.05

MC: Motor Condition, HSC: Healthy Standstill Condition, HRC: Healthy Running Condition, FAGC: Faulty Airgap Condition, AGV: Airgap Variation, MPTSC: Maximum Peak Transient Stator Current, MPTRC: Maximum Peak Transient Rotor Current, RS: Rotor Speed, MPTEMT: Maximum Peak Transient Electromagnetic Torque

All the motor parameter's first transient peak is decreased except electromagnetic torque. The first maximum peak electromagnetic torque is getting increased in the airgap eccentricity faulty conditions as compare to obtained electromagnetic torque in the running motor healthy conditions. Therefore, due to this large irregularity in the airgap, motor's other components may be influenced and might be failed if fault not averted on time. Therefore, it is highly essential to diagnose the change in airgap between the stator and rotor on time. Otherwise, whole industrial plant might be shut down.

4. Airgap Eccentricity Fault Detection by Wavelet Transform

In the present section, the airgap eccentricity fault of the squirrel cage induction motor has been diagnosed by wavelet transform algorithm in the transient condition. Following wavelet's parameters and methods has been used for healthy as well as airgap eccentricity fault diagnosis purpose.

- Data Size: 200002
- Wavelet: Debauchees (dB-10)
- Decomposition Level: 12

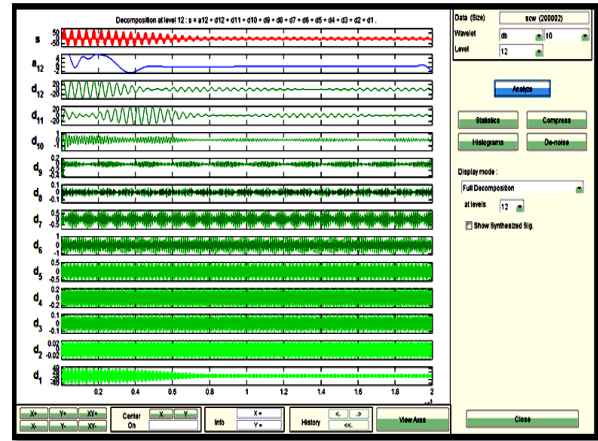
- Wavelet Methods: Full Decomposition, Separate Decomposition, Superimpose Method and Tree Method.

Firstly, the full decomposition method has been applied for airgap eccentricity fault diagnosis purpose. It is as shown in Fig.4(a and b). The sampling frequency has been set 5 KHz. The original stator current signal s has been decomposed upto 12th level of decomposition for healthy as well as for airgap irregularity condition. The decomposed original stator current signal produced two new signals of different frequency bands as shown in Fig. 4(a and b). These two new generated signals are called low frequency approximation signal and other is high frequency detailed signal of stator current. Each new generated stator current signal after decomposition contains its own frequency band. The signal contained high frequency information termed as detailed signal and signal contained low frequency information called approximation signal. The 12th level decomposition has been done for extraction of low frequency information.

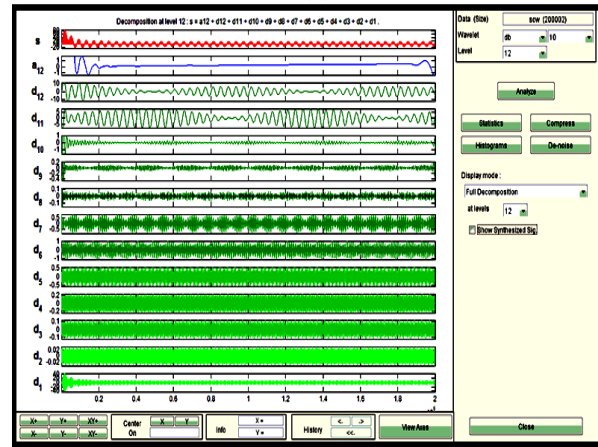
Since, it is highly recommended to use high decomposition levels because for lower decomposition levels, the mother wavelet is located more in time and oscillates faster in a short period of time[6].

The mother wavelet is a prototype and plays most vital role in the wavelet transform. It generates different windows for different frequency bands consequently improved frequency resolution unlike Short Term Fourier Transform (STFT). In this work, A Debauchees (db-10) mother wavelet has been used. Though, No set rule exist to use the mother wavelet till now. But, it has been observed in the deep study and research that the Debauchees mother wavelet is most stable and during reconstruction of the original signal from the wavelet coefficients it does not loose any information. As far as the used wavelet goes to higher levels, it locates less in time and oscillates less due to the dilation nature of the wavelet transform. Therefore, the fast and low type of induction motor faults can be diagnosed with one type of wavelet.

The obtained results by full level decomposition method has been shown in Fig.4(a and b) gives excellent results for healthy as well as 20 % airgap eccentricity faulty conditions. Therefore, due to non-invasive nature of stator current waveforms, we may clearly say that an efficient airgap irregularity diagnosis has been possible by this method.



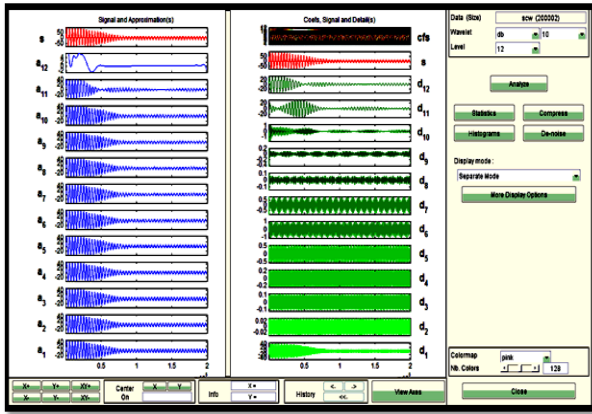
(a)



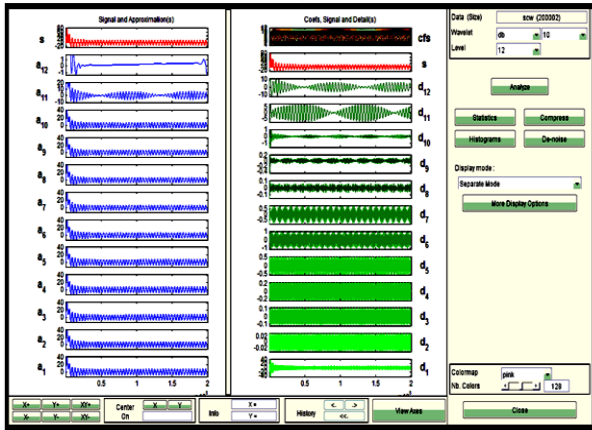
(b)

Fig. 4 (a). Full Level Decomposition of Stator Current, (a) Healthy Condition of the Motor, (b) 20 % Airgap Irregularity Condition of the Motor

The separate decomposition analysis of stator current parameter has been shown in Fig. 5(a and b). Since, the decomposition of the stator current parameter performed upto 12th level for extraction of low frequency information which is hidden in the time domain waveform. Though, the 11th level low frequency approximation signal does not shows much change in the stator current signal but the 12th level low frequency approximation signals contains very significant information. This 12th level low frequency approximation signal contains 1.22 to 0.61 frequency band. Therefore, by the 12th level approximation signal very small frequency fault might be diagnosed. This approximation signal may diagnose airgap eccentricity fault in each and every stage. Therefore; finally, we can say that the separate decomposition method diagnoses very low frequency airgap eccentricity fault in the transient condition by wavelet's approximation signal.



(a)

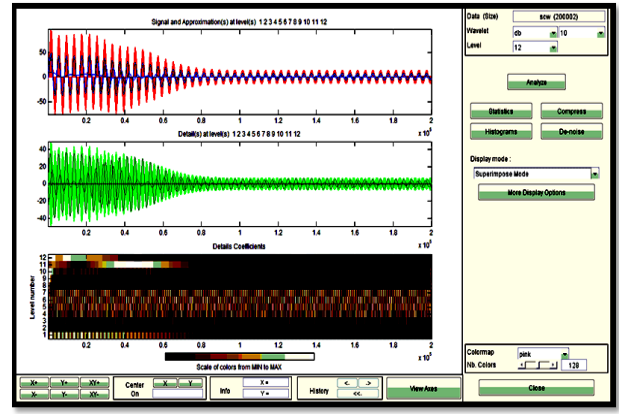


(b)

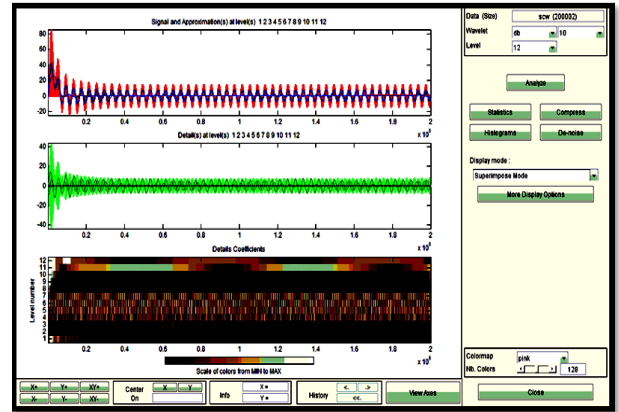
Fig. 5. Separate Decomposition of the Stator Current Signal, (a) Healthy Condition, (b) 20 % Airgap Irregularity Condition of the Motor

The superimpose method has also been applied for the airgap eccentricity fault diagnosis purpose as is shown in Fig. 6(a and b). Both figures waveforms are completely dis-similar to each other. Therefore, the airgap eccentricity fault diagnosis has been done in the efficient way also by this method.

Now, we are choosing only low frequency approximation signal for airgap eccentricity fault diagnosis purpose in the transient condition of the motor. The 12th level low frequency approximation signal has only been considered for airgap eccentricity (20%,30%,40%) irregularity diagnosis purpose. This approximation signal may gives exact results and separated healthy as well as all airgap faulty conditions. Since, in this waveform one tree is formed. Therefore, it is called tree method of the wavelet transform and is as shown in Fig. 7(a to d). From these results, we may clearly analyze the different airgap eccentricity faulty conditions.



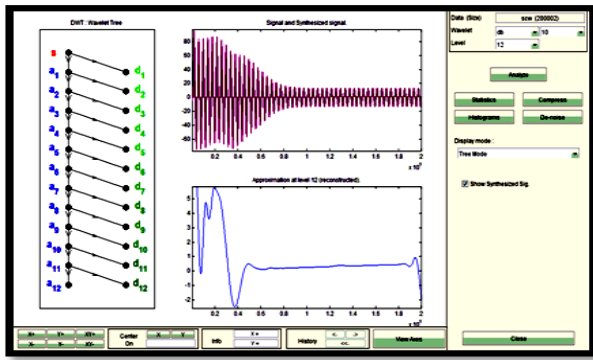
(a)



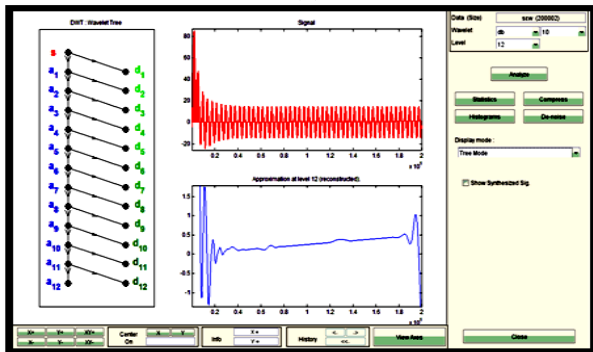
(b)

Fig.6. Superimpose Waveforms for Stator current, (a) Healthy Condition, (b) 20 % Airgap Irregularity Condition of the Motor

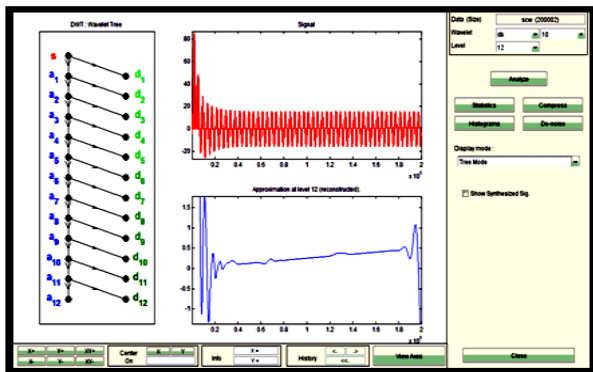
From Fig. 7(a to d), we may understand the difference between healthy and all airgap faulty conditions. First observe the result of healthy condition of the induction motor in Fig. 7(a), this waveform contains three signals: First is stator current source signal, second is wavelet decomposition tree and third is 12th approximation signal. This 12th level approximation signal has been used for the airgap eccentricity fault diagnosis purpose. If we observe the decomposition tree, we may observe that the source stator signal is decomposed and gets two signals these are called first level approximation and first level detailed signal respectively. This decomposition is continued upto 12th level. There, we may have 12th level detailed and 12th level approximation signal. Since, the 12th level low frequency approximation signal contains low frequency information. So, we can diagnose airgap eccentricity fault in the efficient way from final low frequency approximation signal.



(a)



(c)



(d)

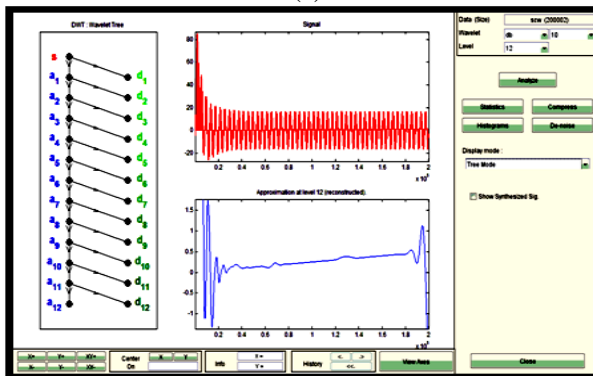


Fig. 7. Approximation Signals of Stator Current (a) Healthy Condition, (b) 20 % Airgap Irregularity Condition of Motor, (c) 30 % Airgap irregularity Condition of Motor, (d) 40 % Airgap Irregularity Condition of Motor

Again observe the Fig. 7(a to d), it has been observed that all figures have been used for airgap eccentricity fault diagnosis purpose; all results are different from each other. Observe the starting and end point of the approximation signal. We may clearly observe that as the percentage of airgap eccentricity increasing in the induction motor, the deviation(harmonics) in the waveforms has also being increased.

Therefore, we can say that efficient airgap eccentricity fault detection is possible in the transient conditions by this method. So, early airgap fault detection is possible. Consequently, the fault may not become more catastrophic and may be averted before happening it. This technique ensures the machine log life, unexpected shut down of the plant and may save large revenues for the industries.

5. CONCLUSIONS

In the present paper, an inverter driven induction motor model has been proposed and used to diagnose airgap eccentricity fault in the transient conditions by time domain and time-frequency domain techniques. Since, the Fast Fourier Transform technique is unable to diagnose airgap eccentricity fault in the transient conditions and also not suitable to diagnose any induction motor fault for varying load. All shortcomings of FFT have been solved by this wavelet transform based novel detection technique of the airgap eccentricity fault. Since, the wavelet transform's several techniques has been used for the airgap eccentricity fault diagnosis purpose. The main advantage of the wavelet transform is that after decomposition of original stator current signal the low frequency suitable information may be extracted which is not previously available. This low frequency information contains very useful information of the airgap eccentricity faulty conditions. The wavelet algorithm is also a non-intrusive technique of the fault diagnosis like other signal processing techniques. Therefore, the superimpose waveform has been successfully used for the airgap eccentricity fault detection purpose. Since, the superimpose waveform contains all the useful information of the airgap eccentricity fault. If we visualize the waveforms obtained by superimpose method we may easily differentiate the healthy and airgap eccentricity faulty conditions of the motor. Finally, we may conclude that the capability of this wavelet algorithm for the early fault detection in the inverter driven induction motor may become most important

technique in the future for the detection of all induction motor faults.

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