Predictive and Standalone Fault Diagnosis System for Induction Motors

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Abstract: Sudden faults created in induction motors result in catastrophic failures and loss of production. Therefore, the industry is in need of a predictive based system that can identify developing faults in advance. Condition monitoring is used as the general method of identifying faults and taking measures before the dreadful situation. However, there is limited work done on the predictive methodologies based on the trend analysis. The study presented in this paper proposes a novel method that identifies trend variation of critical harmonics of the vibration spectrum with increasing fault severity for frequent mechanical faults; structural looseness, misalignment, bearing eccentricity and bearing inner race fault. Faults were artificially induced on a three-phase induction motor and vibration data obtained was analysed with a MATLAB based algorithm.

Keywords: Condition monitoring, Vibration analysis, Fault prediction, Trend analysis

1. Introduction

Induction motors are the most commonly encountered electrical machines in the industry due to their self-starting features, simplicity, reliability, and cost-effectiveness. In failure, it can lead to severe losses due to both, costs of repair or replacement of motor and loss of production. Hence condition monitoring is a critical process for the industry. The well-established approaches for condition monitoring can be classified based on the diagnostic signal such as vibration [1], [2], acoustic [3], thermal [4], motor current [5], [6]. Among them, the vibration signature is the mostly implemented methodology for observing motor malfunctions as the unique vibration patterns assist to identify the root cause of each fault.

Vibration based analysis is the primary technique for predictive maintenance in the industry [7]. Vibration fault simulation systems were implemented to observe vibration patterns before applying the concept in real life [8]. Obtaining vibration RMS (Root Mean Square) is the most traditional way of identifying faults in an induction motor [9]. As a more advanced method, routine tests for motor vibration based on vibration time wave, frequency spectrum, and phase analysis are performed once in a few months. Apart from this, deep learning based vibration analysis techniques have been developed and implemented in the industry for online monitoring [10]. Yet, there is a need for increasing the accuracy of fault diagnosis and

correct prediction of them with an alternative and advanced monitoring system such as trend analysis. When considering vibration, only a few developed techniques can be found on continuous monitoring with trend analysis which is imperative for an industrial perspective [11]. Some comprehensive researches have already revealed that the RMS value of the acquired motor vibration signal can be trended throughout the operating time and early-stage fault detection can be implemented [12]. Considering the easiness of integration with existing machinery and technologies, IoT (Internet of Things) techniques are used for condition monitoring based on both scheduled intervals [13] and real time condition monitoring [14], taking account of the RMS value of the vibration spectrums of induction motors. In addition, there exists wireless vibration monitoring systems instead of wired

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systems for real time measurements of motors [15].

Moving forward, in this research we have identified the trend variations of each critical harmonics of the vibration spectrum for artificially induced faults while scaling up the fault severity. Through that, a novel method can be developed to identify and predict induction motor-based faults.

Here, vibration data is analysed, and trends of variations of harmonics of vibration spectrums are plotted for following faults:

1. Structural looseness
2. Angular misalignment
3. Bearing eccentricity
4. Bearing inner race faults

Experiments for the first three faults were carried out by inducing faults on the developed lab setups and, for bearing inner race faults, a publicly available set of data is used.

2. Proposed Monitoring System

The principle proposed in this research is to capture the growing trend of a motor fault through measuring and online processing of the monitored information based on RMS and critical harmonics values in order to achieve fault identification and prognosis. It includes those particular faults occurring due to the electrical and mechanical stresses which are detectable with this concept. The accuracy and consistent behaviour of this monitoring concept is accomplished through the integration of software and low cost- highly accurate sensors.

3. Implementation of The Proposed Monitoring System

3.1 Data Acquisition Process

Figure 1- Data Acquisition System

Data acquisition was done through a Raspberry-Pi type microcontroller. For vibration data, ADXL345 accelerometer was

used at a sample rate of 3200Hz and a sensitivity of 4mg/LSB. In the setup, two vibration sensors were used for obtaining vibration in axial and radial directions compared with the motor shaft. Further, as a supportive measurement for harmonic identification, motor speed was measured with KY-032 IR sensor. In order to evaluate whether a trend variation can be observed for supply current harmonics, ACS712 Hall-effect current sensor was used with an ADC. Here, Python was used as the programming language for preparing the data acquisition system. The block diagram of data acquisition system is shown in Figure 1. Figure 2 shows the placement of the sensors in the proposed monitoring system.

Figure 2 - Sensor Placement

3.2 Data Analysing Process

It is found through previous works that, for different ranges of expected fault frequencies, vibration measurement technique varies [7]. If we expect to see a spectral line below 10Hz the most effective way is to take the vibration in displacement (m) before taking the frequency spectrum. For most of the induction motor faults, these fault frequencies lie between 10-1000Hz where the velocity spectrum is much more effective.

In this data acquisition system, an accelerometer sensor was used for vibration measurement. Thus, it is essential to take the velocity by integrating it before applying fast Fourier transform. Further, the signal is passed through a low pass filter and a high pass filter. As the amplitudes of harmonics obtained from the vibration spectrum at different occasions are compared, it is essential to eliminate spectral leakage applying to them. So, a windowing function (Hanning Window) is also used. Figure 3 illustrates the block diagram for signal analysis process of the proposed

monitoring system. Data analysing process was done in the micro- controller, programmed with MATLAB. In making the standalone system, the algorithm was converted to a standalone executable and was deployed on the Raspberry Pi microcontroller.

Figure 3 - Signal Analysing Process

4. Fault Analysis

As mentioned earlier, for the four different faults that are simulated in this experiment procedure, different experiment setups and analysing processes were used to create a fault and increase its severity. For each fault, the methodology followed, and the results obtained are discussed below.

5. Structural Looseness

Having bolted joints at the base of a motor causes unintentional loosening as a result of its operational conditions of industries. Therefore, this phenomenon should be identified before it gets worse which can lead to several other severe faults. In the frequency spectrum, looseness can take various forms that are created internally or externally [16]. The most common form of looseness could start with an increase in the amplitude of harmonics of vibration.

5.1 Experimental Setup

Figure 4 shows the three-phase induction motor used to create structural looseness by loosening the above highlighted four bolts which are tightening the motor to the base.

Figure 4 - A Three- Phase Induction Motor Used to Observe Characteristics of Structural Looseness

5.2 Methodology

First, in order to identify how the spectrum is affected by a loosening of bolts, two vibration datasets were collected at normal operation and after loosening all 4 bolts. Both measurements were taken at a running speed of 1500RPM. Then we have considered 4 main scenarios in which the loosening can happen.

Scenario 1: Looseness of one bolt at the drive end

Scenario 2: Looseness of both bolts at the drive end

Scenario 3: Looseness of both bolts at the fan end

Scenario 4: Looseness of all 4 bolts of the motor.

For all these scenarios, the frequency spectrum was obtained while increasing the looseness at an equal phase. Data were obtained in the radial direction at both the drive end and fan end of the motor. Then the amplitudes of the first three harmonics of motor running speeds were plotted against the degree of looseness.

5.3 Results and Discussion

Figure 5 indicates the vibration velocity time signal and frequency spectrums for healthy condition and the worst conditions of looseness respectively, at 1500rpm. A clear increase is observed in the first five harmonics of the vibration spectrum for the faulty motor.

As previously mentioned, in order to critically evaluate the looseness, four scenarios were considered as above and the variations of the

Figure 5 - Vibration Velocity Time Signal and Frequency Spectrum for Looseness Condition

first three harmonics are plotted (Figure 9 to Figure 20).

6. Misalignment

Induction motors which involve industrial processes typically experience misalignment due to various factors such as improper assembly of machines, thermal distortion of machines, asymmetry in applied loads, unequal settlement of the foundation, etc. [17]. For some reason, ultimately, there is an incorrect positioning along the shaft centreline between bearings when two machines are coupled. Types and degrees of misalignment basically depend on coupling type, shaft size, and speed, etc.

6.1 Experimental Setup

Characteristics of angular misalignment was observed using following experimental framework (Figure 6).

Figure 6 - Test Setup to Observe Angular Misalignment

6.2 Methodology

Experiment tests for misalignment fault were conducted in a laboratory environment using a two-pole, 5.5kW, 1500 rpm three phase induction motor. Initially, the shaft of the motor was aligned with the load. Then the shaft was

misaligned by 0.15 mm stepwise and axial vibration was measured. The speed of the motor was kept at 1500 rpm and the coupling type was three- jaw coupling.

6.3 Results and Discussion

Frequency time-domain signals for velocity and acceleration for aligned and misaligned conditions are shown in Figure 7. For correctly aligned condition, frequency velocity spectrum only shows the fundamental harmonic. However, 1x, 2x and 3x harmonics become dominant when the fault is dominant and gives the highest contribution to the vibration of the motor.

Figures 21, 22 and 23 show the patterns of variation for each 1x, 2x and 3x harmonics, respectively. Although all three are increasing, the rates of growth for 1st and 2nd are decelerating and 3rd is accelerating.

7. Bearing Looseness

Bearing eccentricity is a common occurrence due to bearing wear and shaft looseness. It results in an unbalanced force distribution around the bearing. Not attending to this can lead the motor to complete bearing failure or even a winding failure.

7.1 Experimental Setup

In order to simulate a bearing looseness, a separate setup (Figure 8) was developed to exert a force on the shaft which has an induced lump to simulate the bearing wear.

As mentioned, in a bearing looseness, the force is not distributed equally around the shaft. By exerting an external force on the lump created, the fault can be simulated. The setup was developed in a way that it has a rotating element (rubber roller with a bearing) which engages the motor shaft, with the other end

Figure 7- Velocity and Acceleration Vibration for Healthy Condition and Misaligned Condition

fixed to a shock absorber and hence a gradual increase of the force can be applied to the lump. A 5.5 kW rated motor was used here.

7.2 Results and Discussion

Figure 24 shows the velocity vibration of time domain and frequency spectrum for bearing looseness, respectively.

An increase in the first harmonic of the spectrum was expected and it was observed. But an unintentional increase in the 2nd and 3rd

was also observed. It was observed while the bearing looseness is being simulated, due to the push exerted at one side from the coupling point, a parallel misalignment was induced. And the features of a parallel misalignment are the increase in 2nd and 3rd harmonics.

Figures 25, 26 and 27 illustrate 1st, 2nd, and 3rd harmonic variation, respectively, while exerted force is increasing stepwise.

Figure 8 - Detailed Experimental Framework used to Simulate Bearing Looseness

Figure 9 - 1st Harmonic Variation for Drive End One Bolt Loosed

Figure 10 - 2nd Harmonic Variation for Drive End One Bolt Loosed

Figure 11 - 3rd Harmonic Variation for Drive End One Bolt Loosed

Figure 12 - 1st Harmonic Variation for Drive End Two Bolt Loosed

Figure 13 - 2nd Harmonic Variation for Drive End Two Bolt Loosed

Figure 14 - 3rd Harmonic Variation for Drive End Two Bolt Loosed

Figure 15 - 1st Harmonic Variation for Fan End Two Bolt Loosed

Figure 16 - 2nd Harmonic Variation for Fan End Two Bolt Loosed

Figure 17 - 3rd Harmonic Variation for Drive End Two Bolt Loosed

Figure 22 - 2nd Harmonic Variation for Angular Misalignment

Figure 23 - 3rd Harmonic Variation for Angular Misalignment

Figure 24 - Velocity Vibration Time Signal and Frequency Spectrum for Bearing Looseness

Figure 25 - Change in 1st Harmonic While Increasing the Exerted Force in Steps

Figure 26 - Change in 2nd Harmonic While Increasing the Exerted Force in Steps

Figure 27 - Change in 3rd Harmonic While Increasing the Exerted Force in Steps

8. Inner Race Bearing Fault

Bearing failure is considered one of the most common problems for machinery failure. A bearing can fail due to a fault induced at the inner race, outer race and the ball [18].

For bearing inner race faults the critical frequency which shows the spectral line can be calculated from equation (1).

$$BPFI = NF (1 + (d \cos(\emptyset))/D)/2 \quad \dots(1)$$

Where,

BPFI- (Ball Pass Frequency - Inner race)

F - Motor rotating Speed

N - Number of rolling elements in the bearing

d - Diameter of the rolling element

D - Mean diameter of the bearing

$\emptyset$ - Angle of the load from the radial plane

Although velocity spectrums are used for looseness and misalignment detection, as *BPFI* is a considerably large frequency, the spectrum is obtained by directly applying fast fourier transform for acceleration data.

8.1 Methodology

To evaluate how the bearing fault affects the trends of harmonics of the vibration spectrum, external data obtained from a wind turbine

a developing inner race fault is used. It is a 2 MW wind turbine and data are obtained for 50 consecutive days. It has a nominal speed of 1800 RPM fluctuating over the days and these fluctuations are also considered in harmonic detection.

The calculated *BPFI* value for this specific case is 280Hz. Further, in the case of inner race faults, it is a common thing to observe two sidebands around the *BPFI* frequency at running speed. Hence, two sidebands can be observed at 250Hz and at 310Hz. Here, in order to identify how the trend varies with increasing severity, *BPFI* and its sideband amplitudes are plotted against time.

8.2 Results and Observations

The following plots show the two different vibration spectrums at day 1 (Figure 28) and day 50 (Figure 29). It can be clearly identified that there is a huge spike at *BPFI* and considerably large sidebands around them. $2*BPFI$ and $3*BPFI$ are available as well which indicates high severity in Inner race fault.

The trend of variation for *BPFI* and its sidebands are plotted in Figure 30 for the 50-day period.

Figure 28 - Acceleration Vibration Signals in Time and Frequency Domain for 1st Day

Figure 29 - Acceleration Vibration Signals in Time and Frequency Domain for 50th Day

Figure 30 - Frequency Spectrum for Change in *BPFI* and Two Side Bands for 50 Days

9. Conclusions

This research mainly focuses on developing the methodology for condition monitoring based trend analysis. It was found that the proposed method has worked successfully when faults were experimentally tested on actual machines. For all the faults considered in this study, experimental results show that there are specific trend variations of critical harmonics and RMS values of vibration when the severity of faults is increasing. Current harmonic spectrums did not give a clear outcome of a trend at a tested level of the developing each fault. Thus, with continuous monitoring, this trend variation of vibration can be interpreted as slow development of the fault and be alarmed accordingly.

In this way it is possible to create a standalone system powered by a microcontroller to monitor the sensor outputs and identify the trends of variations of harmonics. Then these trends can be used to predict a time of failure in advance. In the future, the proposed concept can be implemented for more fault conditions in induction motors by measuring current and temperature together with vibration.

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References

1. Sendhil Kumar, S., and Senthil Kumar, M., "Condition Monitoring of Rotating Machinery through Vibration Analysis," *J. Sci. Ind. Res. (India)*, Vol. 73, No. 4, pp. 258-261, 2014.
2. Glowacz, A., and Glowacz, W., "Vibration-Based Fault Diagnosis of Commutator Motor," *Shock Vib.*, Vol. 2018, 2018, doi: 10.1155/2018/7460419.
3. Glowacz, A., "Acoustic-Based Fault Diagnosis of Commutator Motor," *Electron.*, Vol. 7, No. 11, 2018, doi: 10.3390/electronics7110299.
4. Gnacinski, P., "Effect of Unbalanced Voltage on Windings Temperature, Operational Life and Load Carrying Capacity of Induction Machine," *Energy Convers. Manag.*, Vol. 49, No. 4, pp. 761-770, 2008, doi: 10.1016/j.enconman.2007.07.033.
5. Li, W., and Mechefske, C. K., "Induction Motor Fault Detection using Vibration and Stator Current Methods," *Insight Non-Destructive Test. Cond. Monit.*, Vol. 46, No. 8, pp. 473-478, 2004, doi: 10.1784/insi.46.8.473.39379.
6. Antonino-Daviu, J. A., Gyftakis, K. N., Garcia-Hernandez, R., Razik, H., and Cardoso, A. J. M., "Comparative Influence of Adjacent and Non-Adjacent Broken Rotor Bars on the Induction Motor Diagnosis through MCSA and ZSC methods," *IECON 2015 - 41st Annu. Conf. IEEE Ind. Electron. Soc.*, pp. 1680-1685, 2015, doi: 10.1109/IECON.2015.7392343.
7. Alsalaet, J., "Vibration Analysis and Diagnostic Guide," No. December, 2012.
8. Gani, A., and Salami, M. J. E., "Vibration Faults Simulation System (VFSS): A System for Teaching and Training on Fault Detection and Diagnosis," *2002 Student Conf. Res. Dev. Glob. Res. Dev. Electr. Electron. Eng. SCORED 2002 - Proc.*, pp. 15-18, 2002, doi: 10.1109/SCORED.2002.1033044.
9. Angelo, M., "Vibration Monitoring of Machines," *Tech. Rev. - Bruel Kjaer English ed.*, No. 1, pp. 1-36, 1987, doi: 10.13140/RG.2.2.19428.42880.
10. Khireddine, M. S., Slimane, N., Abdessemed, Y., and Makhoulfi, M. T., "Fault Detection and Diagnosis in Induction Motor using Artificial Intelligence Technique," *MATEC Web Conf.*, Vol. 16, pp. 6-9, 2014, doi: 10.1051/mateconf/20141610004.
11. Henao H., et al., "Trends in Fault Diagnosis for Electrical Machines: A Review of Diagnostic Techniques," *IEEE Ind. Electron. Mag.*, Vol. 8, No. 2, pp. 31-42, 2014, doi: 10.1109/MIE.2013.2287651.
12. Dinardo, G., Fabbiano, L., and Vacca, G., "A Smart and Intuitive Machine Condition Monitoring in the Industry 4.0 Scenario," *Meas. J. Int. Meas. Confed.*, Vol. 126, No. May, pp. 1-12, 2018, doi: 10.1016/j.measurement.2018.05.041.
13. Yebenbay, Y., and Alimkhan, A., *Vibration Monitoring of Motors*. 2019.
14. Goundar, S. S., Pillai, M. R., Mamun, K. A., Islam, F. R., and Deo, R., "Real Time Condition Monitoring System for Industrial Motors," *2015 2nd Asia-Pacific World Congr. Comput. Sci. Eng. APWC CSE 2015*, No. December, 2016, doi: 10.1109/APWCCSE.2015.7476232.
15. Upadhye, M. Y., Borole, P. B., and Sharma, A. K., "Real-Time Wireless Vibration Monitoring System using LabVIEW," 2015

- Int. Conf. Ind. Instrum. Control. ICIC 2015*, No. Icic, pp. 925-928, 2015, doi: 10.1109/IIC.2015.7150876.
16. Nikraves, S. M. Y., and Goudarzi, M., "A Review Paper on Looseness Detection Methods in Bolted Structures," *Lat. Am. J. Solids Struct.*, Vol. 14, No. 12, pp. 2153-2176, 2017, doi: 10.1590/1679-78254231.
 17. Kumar, C., Krishnan, G., and Sarangi, S., "Experimental Investigation on Misalignment Fault Detection in Induction Motors using Current and Vibration Signature Analysis," *2015 1st Int. Conf. Futur. Trends Comput. Anal. Knowl. Manag. ABLAZE 2015*, pp. 61-66, 2015, doi: 10.1109/ABLAZE.2015.7154971.
 18. Saruhan, H., Saridemir, S., Çiçek, A., and Uygur, I., "Vibration Analysis of Rolling Element Bearings Defects," *J. Appl. Res. Technol.*, Vol. 12, No. 3, pp. 384-395, 2014, doi: 10.1016/S1665-6423(14)71620-7.