Condition monitoring of 3-phase induction motor

Sujindharan Narayanasamy
School of Engineering
Asia Pacific University of Technology and Innovation (APU)
Kuala Lumpur, Malaysia

Chandrasekharan Nataraj
School of Engineering
Asia Pacific University of Technology and Innovation (APU)
Kuala Lumpur, Malaysia

Ravi Lakshmanan
School of Engineering
Asia Pacific University of Technology and Innovation (APU)
Kuala Lumpur, Malaysia

***Abstract*—A system has built to monitor conditions of a 3-phase Induction motor. The purpose of the system is to detect fault when the Induction motor is being operated. To build a fault detection system various methods have been used in this work. A prototype setup has built to test and evaluate the results of the developed system. The first method used to develop the system was through current monitoring where sensors used to monitor the current drawn by the 3-phase Induction Motor while operating on non-faulty and faulty conditions. Vibration sensor was used to monitor vibrations from rotating shaft on no-fault and fault conditions and Vibration Energy Harvester setup was made and equipped with the system. Vibration Energy Harvester (VEH) was acquiring vibration from the rotating shaft to generate signals to feed into the system. Results were obtained from the methods used to monitor the 3-phase Induction Motor during both no fault and fault conditions. Appropriate threshold values set to all methods used to monitor condition of the 3-hase induction motor. The results obtained shows that all three methods can be used to monitor condition of 3 -phase induction motor but the stability and reliability of the results obtained differs from one another.**

Keywords — Induction motors, conditioning monitoring, vibration, energy harvester, stability, current sensors.

I. INTRODUCTION

Community prosperity is frequently measured by the capacity to generate products and services. The production of these two uses a great deal of energy and the use of energy needs to be smart. Energy comes in many ways, including mechanical energy, thermal energy, kinetic energy, and electrical energy. For the production of heat and light, electrical energy is partially used and this form of energy is measured in kilowatt hour (kWh). Other cases are the transformation of electrical energy in electric motors into mechanical energy. Induction motors are the most common motors in industry and home appliances among the motors used.

Traditionally, induction motors were supplied straight from the power supply, which is a 3-phase alternating current using the suitable protections of the electromagnetic power switches. There are more than 3kW of electric motors per individual in developed countries and most of them are induction motors. The induction motor power is transformed into variable speed drive implementation in developed countries. This enables the user to differ the induction engine velocity depending on the implementation for which it is being used.

Most of the condition monitoring process would be to monitor specific parameters such as vibration, overheating and current equipment for early signs of failure as well as for maintenance purposes to be required prior to the rigorous failure and estimate overall health of the machines. This includes the machine parts ' life system, distinct techniques of data acquisition, and information exploitation to forecast trends. For ongoing process plants where breakdowns can be very expensive, condition monitoring is primarily suitable and necessary. Before the condition monitoring scheme, the method used for preventive maintenance was time-based maintenance. In this method the maintenance is carried out on the equipment's predefined running hours without the information of the machine's current conditions. This resulted in manpower, time and money wasted [1].

In summary, with low failure rates, induction motors are very reliable and require only fundamental maintenance, like any type of engines that break down and fail sometimes. These engines unexpected breakdown may cause a lot of unacceptable loss. Certainly, the breakdowns of these are unacceptable in the implementation of induction engines that are very essential to any sector. Detecting these failures in the initial stages and replacing the damaged parts as scheduled will prevent the machine's unexpected breakdown problems. Preventing unplanned downtime for these electrical drive systems has been the goal of each industry and this will reduce maintenance-related costs.

II. LITERATURE REVIEW

The system has developed using vibration signals to perform bearing failure diagnosis in induction motors [2]. It is stated that faults in bearing can be classified into distributed and localized defects. Distributed failures affect an entire region and are hard to characterize by their spectrum of frequencies. The model suggested an improved bi-spectrum method with an auxiliary frequency injection to monitor engine health status induction [3]. There were two primary components of this study, first Auxiliary Injection and then Enhanced Bi-spectrum. The auxiliary injection was intended to enhance features related to fault and enhanced bi-spectrum is intended to extract representative features for incipient detection of bearing fault [4].

It is proposed a real-time condition monitoring system for industrial motors, using a piezoelectric sensor or simply an accelerometer it's light weight, simple positioning and setup has made the sensor very helpful here. Microcontroller was used to obtain data, process data, store information on the local cloud server and alert the user to error detection [5].

The fault detection scheme is proposed for Nuclear Power Plant induction engines. Here, rotor and bearing faults were the focus of the studies. This research focused primarily on bearing failure where the fault consisted mainly of outer race and inner race, cage and also balls. The fault was defined here as a ball defect, an external raceway defect, and an internal raceway defect. Bearing fault mostly on the race and there is a relationship between the bearing vibration and the current stator spectra that can be determined by the eccentricity of the air gap [6].

The researcher used discrete wavelet transformation and deep neural networks to diagnose gear failure. Deep neural network with many hidden layers is a conventional multilayer perceptron. To extract discriminative features, this method was used. Training the Deep Neural Network will make the extraction characteristic map more robust against various variables, resulting in a precise diagnostic scheme. Discrete Wavelet Transform was used here because it offers a time-scale representation that is a helpful instrument for analysing a signal shift by locating the frequency contents of the specific signal in time [7].

A Dyadic Wavelet Transform based on acoustic signal analysis was proposed here by researchers. The acoustic signal emitted from the rotating electrical machines was categorized as electromagnetic noise, mechanical noise, aerodynamic noise, and electronic power device noise. The magnetic flux travels radially across the air gap between the stator and the rotor in a 3-phase induction motor. This results in radial forces that cause distortion, resulting in vibration and noise. If any of the radial force coincides with the machine's natural frequency, resonance occurs, which results in electromagnetic noise [8].

An unbalanced magnetic pull monitoring and damping is proposed due to induction machine eccentricity deficiency. In an induction motor, unequal air gap between the stator and the rotor results in rotor eccentricity [9]. It also produces an electromagnetic force from stator to rotor. This force depends in terms of angular velocity on the movement rotor axis away from the stator axis and the movement of the eccentric rotor. Winding arrangement, loading and slotting will cause effects. This force acts irregularly between the rotor and stator, pulling the rotor out of its fixed location, causing misalignment, which is called an unbalanced magnetic pull [10].

Stator Current Signature Analysis for Monitoring Shaft Misalignment in Induction Motor Speed Controlled. Misalignments are classified as mechanical deficiencies. This will affect both the level of the vibration and the pattern. The second harmonic frequency and rotation frequency will notify this. You can even categorize this vibration into radial misalignment or angular misalignment. It also suggested using harmonic present and acoustic noise to detect mechanical induction engine flaws. The research concentrated more on the rotor's eccentricity through harmonic and acoustic noise. General eccentricity can be divided into three types like static eccentricity, dynamic eccentricity, and eccentricity mixing.

The research proposes a system that detects an induction motor failure by using smartphone audible noise recorded. Different conditions of motor failure were measured in this research based on broken rotor bars and healthy condition. The broken rotor bars were simulated by drilling a hole through a number of rotor bars respectively. For Dynamic Eccentricity (DEC), the rotor was moved 28% of the length of the air-space using an additional ring between the shaft and the bearing. The condition of loose bearing has been achieved by simply increasing the bearing diameter. During the tests, all the electrical data of the induction motor under investigation were measured and the mechanical vibration sensors mounted on the engine circumference were recorded [11].

Smart energy use results in greater productivity with reduced energy consumption and reduced losses. Reducing the losses from the use of the engine will decrease the effect on the environment where the heat and chemical effects at the power plant producing the electrical energy required. The use of induction motors at different speeds by varying the frequency with drivers adds to the present pollution of harmonics in the power grid and electromagnetic interference [12].

Two kinds of engine induction, squirrel cage and wound rotor are available. The stator and rotor windings are produced of separately insulated coils in a wound rotor induction motor and the rotor coils are made available by means of slip rings to the stator side. The rotor windings are replaced by longitudinal bars in the slots of the rotor exterior surface in the squirrel cage devices. Both the motors have stator windings generate a rotating magnetic field when it is supplied an AC current.

Electrical machines are the main generators of mechanical power. Although the design takes into account of the possibility of the most typical faults, such as overvoltage and overcurrent, it is possible that the electrical machine holds out the normal status during all the its life span. A fault in the machine causes a nonprogrammed stop in the process, with the serious economic consequences. It also using time-domain analysis, indicators can be created for bearing failures in their early stages as indicators are highly likely to vary with load profile or application. For this case, methods of the frequency domain are suitable techniques for detecting bearing failure and its diagnosis. Fault-related characteristic frequency components in a spectrum observe bearing condition [13].

The review has provided various analysis that can be conducted on an induction motor for condition monitoring and fault detection. Condition monitoring of an induction motor should include fault detection under the system. This is to ensure the user operates and maintains the induction motor with ease and there will be no fault diagnosis done by the employees as the fault of the induction motor has been already diagnosed. This will ensure safer and efficient way to operate an induction motor in any industry. It does not surf the purpose of condition monitoring of a 3-phase induction motor when the system is not equipped with fault detection system. Condition monitoring can be done in many ways mainly focusing on bearing fault and rotor faults because these two parts tend to fail easier than other parts of the motor. This is because a rotating part of any machine is easier to fail than the non-rotating or moving part.

III. Proposed System and Its Operations

The flowchart shown in Fig.1 is the proposed methodology for this project. The project is on condition monitoring of a 3-phase induction motor where faults present and occurred in the motor will be detected. To start off with the induction motor needs to be switched on manually. The motor then runs at a certain speed where the frequency of the motor will be set to a suitable point. The developed system then collects signals from the running motor for condition monitoring with the help of sensors.

The collected signals are then sent to the microcontroller for decision making. In the microcontroller the acquired signals go through filters where it detects if the signal processing results have exceeded the threshold set. If the threshold is not exceeded, then the system continues to collect signals from the sensors. If the signal has exceeded the threshold limit of the filter, then the system proceeds with further signal analysis. The signal processing works parallel with the microcontroller to perform vibration signal analysis and current signal analysis.

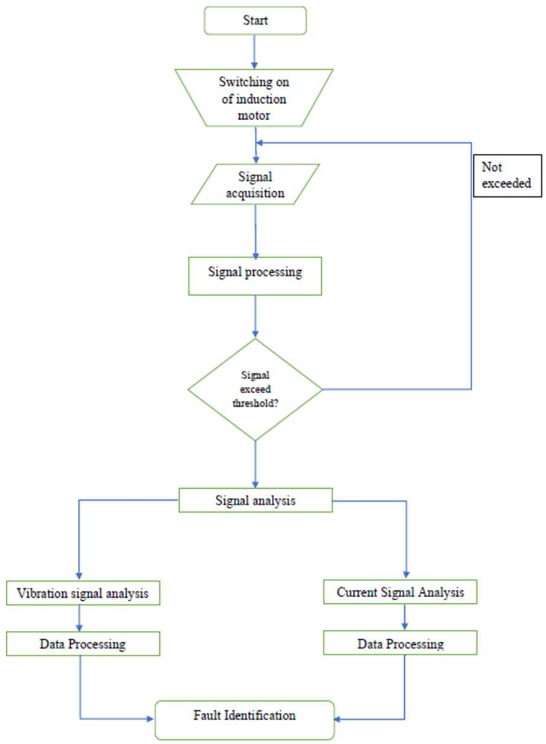

Fig. 1. General Block diagram

Vibration signal is acquired using vibration sensor which will be attached to an induction motor. The position of sensor attachment is very important as it might be collecting irrelevant signals from the surrounding or a vibration from a normally operating induction motor. Sensor needs to be calibrated here to obtain a good signal from the running induction motor for further processing. The vibration signal processing has its own threshold set where each range of frequencies will be indicating a particular fault present in the running induction motor. Once the signal processing is done and fault is detected the system let the user or the machine operator know what is the fault present. Another branch of the parallel working system is that the current sensor collects signal for the microcontroller for further analysis.

The current signal analysis process the current signal from the sensor which is connected to the motor circuitry appropriately. This signal analysis is regarding the current that flows through the induction motor. The current analysis can be used to detect faults present in the induction motor. The sensor here needs to be calibrated accordingly and tested to ensure good current signal analysis is done by the system. Processed signal from the system indicates the faults present in the induction motor and give information to the user. to get image processed and computer vision.

A. Block Diagram

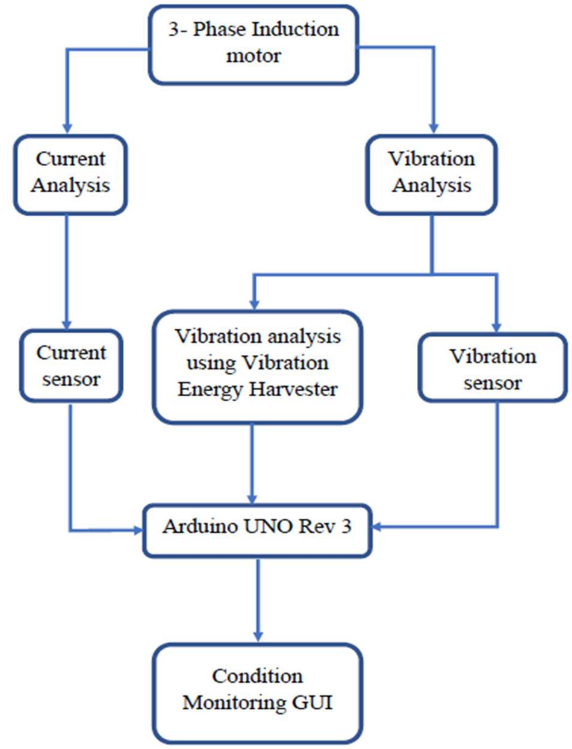

Fig. 2. Block diagram for MATLAB Platform

The block diagram shown in Fig. 2 demonstrates the prototype design of the proposed system. The 3-phase Induction Motor at the top is being analysed via vibration analysis and current analysis. Current analysis uses the current sensor to collect data on current whereas in vibration analysis section there is two different methods used. One being the traditional vibration sensor and another one is the vibration energy harvesting method. The sensors will feed to the Arduino UNO Rev 3 microcontroller where it then sends the data to the Condition Monitoring GUI. In the GUI the user is allowed to set the maximum threshold value for the vibration and current sensors. This feature was set because there are various types of Induction motors with vast number of ratings. To accommodate most of the Induction motors the GUI was made such.

B. Working Principle:

The 3-phase Induction motor is excited with the running frequency of 55hertz by controlling the motor inverter. 3-phase Induction Motor then spins and rotates the bearing attached to the shaft. This condition is set to be the normal condition where it is assumed no fault is present. In between the bearing there was a wheel placed to simulate errors. Simply by adding bolts or weights to the wheel will create an imbalance effect on the motor rotation. This causes vibration to increase. By increasing the vibration fault is then analyzed via the methods stated earlier. The increase in vibration from the rotation will make the magnets in Vibration Energy Harvester setup to vibrate in a fixed position creating a change in magnetic field. The coils then get induced current by the vibration of the magnets. The magnitude of induced current depends on the intensity and frequency of the vibration from the rotating Induction motor with simulated fault. In normal conditions there will be induced current but will have a lower magnitude. Vibration sensor ADXL 335 will also react towards the simulated vibration using the bolts or weight to the wheels and shows its changes in reading. The current sensor on the other hand will be sending current readings to the Arduino Uno Rev3. The current reading was for each phases and it shows the current drawn by the 3-phase Induction Motor on no-fault and fault conditions.

The Vibration Energy Harvester (VEH) setup, vibration sensor ADXL 335 and YHDC sct-013-000 current sensor reading were fed into dedicated Arduino Uno Rev 3. Each Arduino Uno 3 microcontroller was then connected to the system constructed for the monitoring and fault detection process. The system constructed has a GUI that will show errors if the readings from the sensors are exceeding the values set by the user. As mentioned earlier the fault threshold can be changed according to the machine that this system being equipped with this provides flexibility to the user to adjust and set the thresholds accordingly. For this setup build the threshold values were set. The vibration sensor ADXL 335 readings should not be more than 2 G values and the VEH setup readings obtained should not be exceeding 2.5 V. This threshold was maintained throughout the testing period and results were obtained.

C. *Prototype Design*

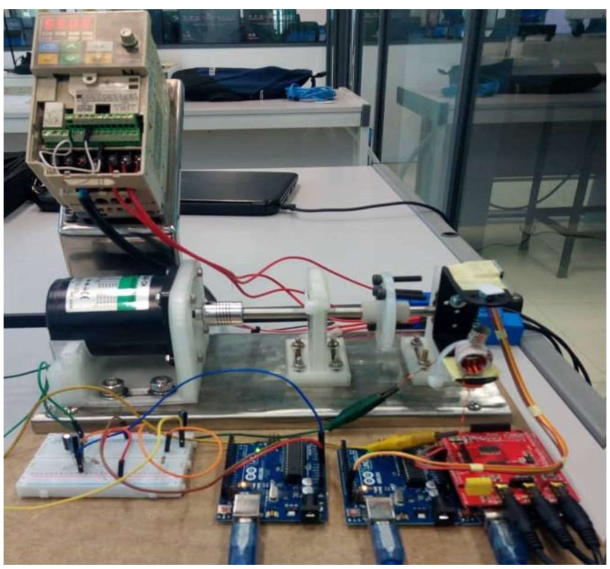

Fig. 3. Hardware Prototype for induction motor conditioning monitoring

Condition Monitoring of 3-phase Induction Motor prototype was made as shown in the Fig. 3. By observing the hardware design, there are Motor inverter or frequency driver in other words being used here to operate the 3-phase Induction Motor. The 3-phase Induction Motor operates on 220Vac for each phase. The motor was coupled with a 8mm diameter shaft to two bearing holders. A wheel was placed in between the bearing holders to simulate and introduce fault to the prototype setup. The bearing holder on the right (end) has aluminium bracket mounted to it to attach the magnets and the vibration sensor. As observed the wheel has screws in this picture. The screws were used to introduce errors to the rotating shaft which will cause vibration. The Induction Motor was operated at a frequency of 55Hz as Malaysia uses frequencies from 50 Hz to 60 Hz.

The wheel placed in between the bearing holders on the shaft. The holes on the wheels were made to accommodate the screws for fault testing. Here the screws are considered as the fault where it creates an imbalance effect on the rotating shaft. Which then vibrates the setup and the vibration was sensed by vibration sensor (ADXL335) and Vibration Energy Harvester setup made. The aluminium mount on the bearing holder and the magnet placed at the bottom of the aluminium bracket can be observed in the red box highlighted. The coil was placed in between the magnets to obtain more induced voltage as possible from the setup made.

IV. Performance Testing and simulation results

The overall performance of the developed system has been evaluated by conducting various simulations and relevant tests.

A. *Current sensor test*

In this test, the current sensor used in the prototype are tested. Three units of current sensor YHDC sct-013-000 was used here to measure current at for each phase that was supplied to the 3-phase Induction Motor. This test was to determine that by measuring current drawn by the Induction Motor the fault can be detected. The higher the load or vibrations, the higher the drawn current by the 3-phase Induction Motor.

The sample results were obtained for 20 intervals on both operating conditions. Observing the table, the value changes can be noticed for different operating conditions. Small change in the current drawn by the 3-phase Induction Motor can be observed through this test.

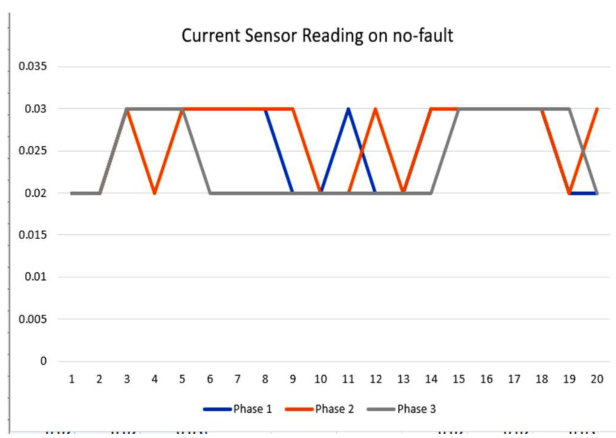

Fig. 4. Current reading on no-fault condition

Observing the above Fig. 4, the graph has been fluctuating in the range of 0.02A to 0.03A on no-fault running condition of the 3-phase Induction Motor. Fluctuation of the current drawn by each phase was plot in above graph to observe the changes and the consumed current while motor was running. The current drawn has changes in a random fashion where it does not have a pattern.

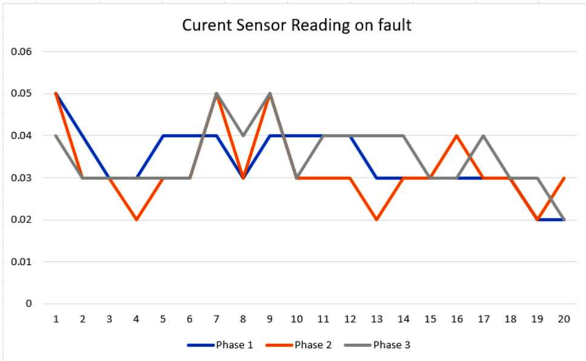

Fig. 5. Current reading on fault detection

Fig. 5 shows the graph waveform of the current consumed by 3-phase Induction Motor while operating on fault condition. The readings obtained was having a higher range of current where it ranges from 0.02A to 0.05A. The starting current of Induction motor for all three phases was 0.05A which is more than the starting current of the induction motor while operating on no-fault condition. This is because the motor has more load on the fault condition, the fault introduced in this test acts as a fault and also it also being the load to the 3-phase Induction Motor. The graph shows the motor consumed higher current for all three phases which can be concluded because of the fault introduced into the prototype setup condition which was fault condition. The higher the load or vibrations caused by the Induction Motor, the higher the current drawn by the motor.

B. Vibration sensor test

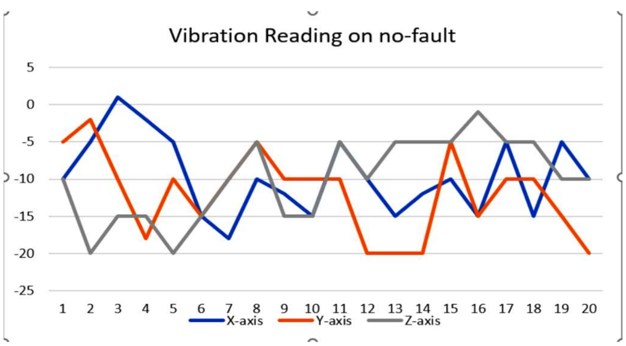

Fig. 6. Vibration reading on no-fault condition

The Fig. 6 shows the waveform obtained from conducting Vibration Sensor test using ADXL335 vibration sensor. This sensor is a three axis sensor where it will measure the gravity force acting of each direction of the sensor. The sensor response very quickly where the readings fluctuate at a very high rate which contributes to the waveform of the above image. The values obtained ranges from +2 G to -20 G. Fluctuation with this high rate makes obtaining or observing the reading harder. The sensor can be said to be very sensitive and the sensor should be used for position movement for example on a Humanoid Robot stabilizing system where the system helps it to stabilize the robot. ADXL335 will be more suitable to for movement based sensing rather than rotation sensing.

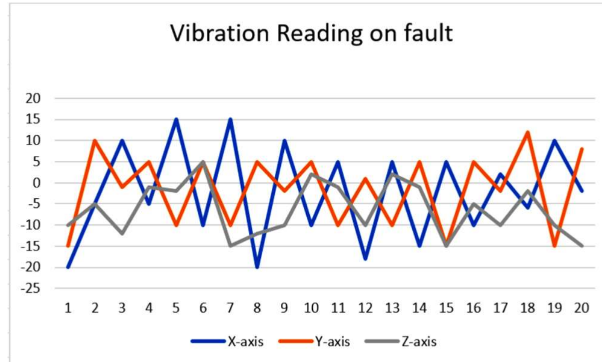

Fig. 7. Vibration reading on faulty condition

The Fig. 7 shows the graphs obtained from the fault condition on the Vibration Sensor test. The graph has a very random waveform which has very high fluctuation of values. The reading goes from -20G to 15G. Observing this waveform shows that the fault condition can be detected using Vibration Sensor (ADXL335). Readings from this setup shows fault being detected.

C. Vibrartion energy harvester set up

The proposed vibration sensor setup was made as an alternative solution to the existing vibration sensor. This setup was done by using magnets, coils and an amplifier circuit to amplify the signal obtain at the coils. There were two magnets used in the setup as mentioned earlier one hanging on spring attached to the aluminum bracket attached to the bearing holder and another magnet was placed directly below the hanging magnet with a certain amount of gap to ensure there is a slight attraction between these magnets. The magnets should not be too close to each other as it will get attracted and detaches the spring by itself. These magnetic field in between the magnets was used to induce voltage in the coil. As the motor runs there was slight vibration which was assumed to be the normal running condition of the motor, once the fault was introduced to the prototype the hanging magnet vibrates and causes change in magnetic field and gets the coil induced voltage.

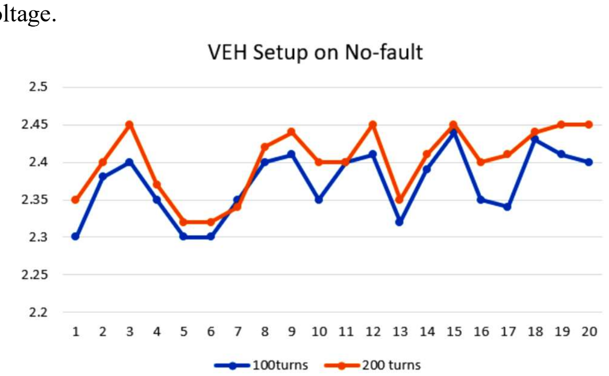

Fig. 8. VEH setup reading on no-fault condition

This induced voltage in the coil was sent to an amplifier circuit because the voltage was in millivolt range. The amplifier then amplifies the signal fed to by 100 and sent it to Arduino Uno Rev3 Microcontroller. The higher the voltage obtained the higher the vibration is and the range was set 0V to 2.45V was set to normal condition, 2.45V to 2.50 V was assumed to be the marginal fault range and any value more than 2.50V was set to be faulty range. Here only the coil size was manipulated and other parameters for example the copper wire thickness was kept constant for coils made which is 0.51mm, inner diameter of the coil was kept constant to 13mm for coils made.

Fig.8 shows the waveform plotted from the date obtained on the no-fault condition. Orange waveform represents 200 turn coil and blue 100 turn coil. The 200 turn coil was able to Harvest Energy Higher than the 100 turn coil. On no-fault running condition the magnet has a lower vibrating rate with more movement. This makes the rate of magnetic field change to be low.

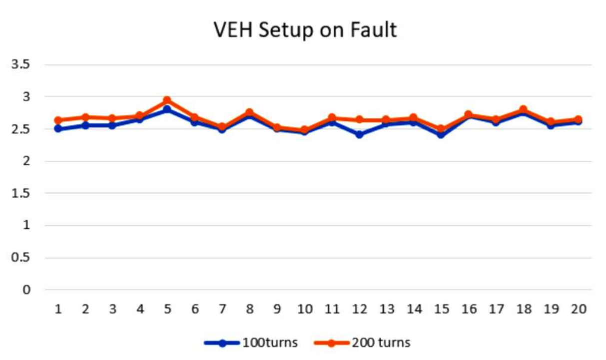

Fig. 9. VEH setup on fault condition

Fig. 9 shows the waveform from the Vibration Energy Harvester (VEH) setup on-fault condition. Waveform of this graph was slightly smoother than the no-fault condition waveform but this has a higher voltage reading. Voltage reading which exceeds 2.5V was assumed to indicate fault present in the setup. In this case, the voltage readings obtained indicated fault. The waveform at no-fault was having readings up to 2.45V which was set to be marginal fault as mentioned in earlier sections. On fault condition the VEH setup produced a higher reading which indicates fault present in the setup. Thus fault can be detected.

D. *Efficiency of Vibrartion energy harvester compared with vibration sensor*

In this test, ADXL335 vibration sensor and Vibration Energy Harvester setup was tested simultaneously where the fault and normal running condition was tested. Test was conducted to show the ability of the Vibration Energy Harvester to measure or detect vibrations. The waveform of both analyses through vibration is illustrated in Fig. 10 shows the differences between the setups for the same applications and to show its ability. The Vibration sensor reading shows fluctuations throughout the testing period. The VEH on the other hand showed less fluctuations and a stable reading (indicates fault was obtained). The fault voltage for VEH was set to be higher than 2.5V, here the waveform of VEH setup shows the error. Vibration sensor in this case its drawback where it fluctuates which makes the setup to have a lesser reliability than VEH setup which has both stable results and it indicates fault on fault condition. As observed the readings differ from one another. The VEH setup has a small fluctuation in readings obtained but all the reading was indicating fault whereas the vibration sensor ADXL 335 was fluctuating at a very high rate. This caused the reading obtained from it to be in the fault range and no-fault range when the test was conducted in fault condition.

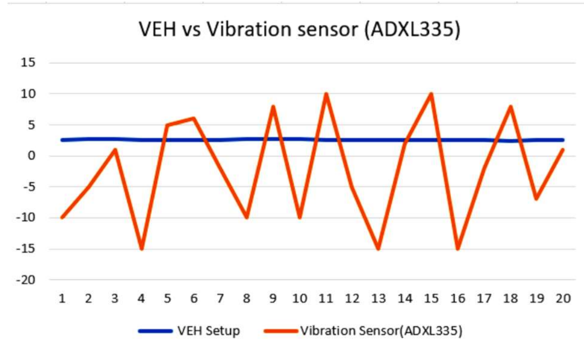

Fig. 10. VEH vs Vibration sensor reading

System that uses alarm for Vibration Sensor (ADXL335) setup would have a random switch on and off of alarm causing confusion in Condition Monitoring of 3 phase Induction Motor. the VEH setup on the other hand has stable output and can be setup with and alarm system and it would not have a random switch on and off of phenomena when fault occurs. In other words, the vibration sensors (ADXL335) shows there is present of fault and no present of fault by fluctuating with this range of values whereas the VEH setup build shows a stable error signal or fault present to the user.

V. CONCLUSION

The condition monitoring of 3-phase Induction Motor has developed and demonstrated using prototype model. The performance of the system is evaluated through the prototype that incorporates Node-Red and Arduino IDE software to display the readings obtained using sensors and VEH setup. A fault detection system for 3-phase induction motor was constructed by setting up threshold values based on the preliminary tests. The threshold was set based on fault and the no-fault reading obtained by the system using the sensors. The performance analysis also conducted by comparing the results of no fault and fault conditions. Finally, it is proved that the developed system provides more reliable results for conditioning monitoring of induction motors.

REFERENCES

[1] A.Salah, Y. Guo and D. Dorrell, “Monitoring and damping unbalanced magnetic pull due to eccentricity fault in induction machines: A review," 20th International Conference on Electrical Machines and Systems (ICEMS),2017.

[2] B. Yan, C. Zhang and L. Li., “Design and Fabrication of a High-Efficiency Magnetostrictive Energy Harvester for High-Impact Vibration Systems”, IEEE Transactions on Magnetics, 2015.

[3] D. Z. Li, W. Wang and F. Ismail, “An Enhanced Bispectrum Technique With Auxiliary Frequency Injection for Induction Motor Health Condtion Monitoring”, IEEE Transactions on Instrumentation and Measurements, 2015.

[4] J. Qiu, X. Liu, H. Chen, X. Xu, Y. Wen and P. Li, “A Low-Frequency Resonant Electromagnetic Vibration Energy Harvester Employing the Halbach Arrays for Intelligent Wireless Sensor Networks”, IEEE Transactions on Magnetics, 2015.

[5] L. A. J. Friedrich, J. J. H. Paulides and E. A. Lomonova, "Modeling and Optimization of a Tubular Generator for Vibration Energy Harvesting Application", IEEE Transactions on Magnetics, 2017.

[6] M. Heydarzadeh, S. H. Kia, M. Nourani, H. Henao and G. Capolino, "Gear fault diagnosis using discrete wavelet transform and deep neural networks", In-IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, (Florence), 2016.

[7] M. J. M. Gonçalves, R. C. Creppe, E. G. Marques and S. M. A. Cruz, "Diagnosis of bearing faults in induction motors by vibration signals - Comparison of multiple signal processing approaches", IEEE Xplorer, 2015.

[8] P. Sangeetha and S. Hemamalini, "Dyadic wavelet transform-based acoustic signal analysis for torque prediction of a three-phase induction motor", IET Signal Processing, 2017.

[9] Q. Gao, W. Zhang, H. Zou, W. Li, Z. Peng and G. Meng, "Design and Analysis of a Bi-stable Vibration Energy Harvester Using Diamagnetic Levitation Mechanism", IEEE Transactions on Magnetics, 2017.

[10] S. S. Goundar, M. R. Pillai, K. A. Mamun, F. R. Islam and R. Deo, "Real time condition monitoring system for industrial motors", 2nd Asia-Pacific World Congress on Computer Science and Engineering (APWC on CSE), 2015.

[11] S. Prainetr, S. Wangnippanto and S. Tunyasirut, "Detection mechanical fault of induction motor using harmonic current and sound acoustic", International Electrical Engineering Congress (iEECON), 2017.

[12] T. Vaimann, J. Sobra, A. Belahcen, A. Rassõlkin, M. Rolak and A. Kallaste, "Induction machine fault detection using smartphone recorded audible noise", IET Science, Measurement & Technology, 2019.

[13] W. He, J. Zhang, S. Yuan, A. Yang and C. Qu, "A Three-Dimensional Magneto-Electric Vibration Energy Harvester Based on Magnetic Levitation", IEEE Magnetics Letters, 2017.