MECHANICAL VIBRATION ANALYSIS OF ELECTRICAL MACHINES AND ITS OPTIMIZATION TECHNIQUES

DISSERTATION II

Submitted in partial fulfillment of the
Requirement of the award of the
Degree of

MASTER OF TECHNOLOGY
IN
(Electrical Engineering)

By

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Under the Guidance of

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Ms. KAVITA DUBEY

Project Supervisor

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ABSTRACT

The main aspect of the work is to optimize the efficiency and performance of an electrical device by capturing and analyzing its mechanical vibrations. This can be done with various methods. Here mention various methods as fast Fourier transform, various mathematical analysis like mean, variance, standard deviation, skewness, kurtosis and fuzzy logic . In this work, some advanced method using Fast Fourier Transform Analysis is discussed in detail.

The HVAC (Heating, Ventilation and Air Conditioning) system is analyzed here. The concept of damping these vibrations is related to the analysis and modeling of these vibrations. In generally, data is captured using the motion sensors or vibration sensors firstly, then it is analyzed. On next, the controller decides the solution for the problem. Sometimes it might be a control signal to the controller or a warning pop out in the monitoring system depending up on the characteristics of the vibration. This action is related with the vibration scales, frequency analysis bandwidth and the addition and subtraction of the decibels. The bandwidth of the vibrations is also plays a vital role in the controlling of the system.

In this work, a controller is designed to deal with the analysis of the vibration signals. The simulation of the system is done with MATLAB. The requirement of these controllers is to provide a more stable and reliable performance and helps the system to regain its normal value after any disturbance.

ACKNOWLEDGEMENT

I am grateful to the individuals who contributed their valuable time towards my Dissertation1 I wish to express my sincere and heart full gratitude to my guide **MS. KAVITA DUBEY,** Assistant Professor, Department Electrical Engineering who guided me to take up this pre dissertation in sync with global trends in scientific approach.

I am also grateful to Lovely Professional University for providing me an adequate infrastructure and facilities to carried out the investigations.

SANDEEPAN. C

Reg. No. 11307629

Date: 5 MAY, 2015.

CERTIFICATE

This is to certify that **SANDEEPAN. C** bearing Registration no.11307629 has completed objective formulation of thesis titled, "**Mechanical Vibration Analysis Of Electrical Machines And Its Optimization Techniques**" under my guidance and supervision. To the best of my knowledge, the present work is the result of his original investigation and study. No part of the theses has even been submitted for any other degree at any University.

The thesis is fit for submission and the partial fulfillment of the conditions for the award of **MASTER OF TECHNOLOGY (POWER SYSTEMS).**

Ms. KAVITA DUBEY
Lovely Professional University
Phagwara, Punjab.

Date: 5 MAY, 2015.

DECLARATION

I, SANDEEPAN. C student of MASTER OF TECHNOLOGY (POWER SYSTEMS) under Department of ELECTRICAL ENGINEERING of Lovely Professional University, Punjab, hereby declare that all the information furnished in this thesis report is based on my own intensive research and is genuine.

This thesis does to the best of my knowledge, contain part of my work which has been submitted for the award of my degree either of this university or any other university without proper citation.

Date: 5 MAY, 2015.

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LIST OF ABBREVIATIONS

HVAC	-	Heating Ventilation and Air Conditioning
RMS	-	Root Mean Square
MEMS	-	Micro Electro Mechanical System
PMSM	-	Permanent Magnet Synchronous Motor
DWT	-	Discrete Wavelet Transform
ART2 NN	-	Adaptive Resonance Theory-2 Neural Network
PID	-	Proportional Integral Derivative
NC	-	Numerical Control
ANN	-	Artificial Neural Network
FFT	-	Fast Fourier Transform
IFFT	-	Inverse Fast Fourier Transform
SDOF	-	Single Degree Of Freedom
DFT	-	Discrete Fourier Transform
ASCII	-	American Standard Code for Information Interchange
SCADA	-	Supervisory Control And Data Acquisition

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1. INTRODUCTION

The mechanical vibration analysis of electrical devices have became a major area in improving the performance and efficiency of the system. In this work, a detailed study of vibration data from an HVAC (Heating, Ventilation and Air Conditioning) system is carried out and controller is designed for the optimized system. Various parameters like frequency domain, mean, variance, standard deviation, etc are analysed for the optimized result. The basic of these strategies include data capturing, analysis and formation of control signal to the controller. In this work, discussion about these techniques and strategy used for the controller action is carried out.

Consider any kind of mechanical vibration processed by any electrical machine. What is a mechanical vibration? In simple words, it can say that mechanical vibrations are oscillatory behaviour of mechanical bodies. For this oscillatory motion to exist, a body must possess inertia and elasticity when an external force is applied. In case of electrical devices, this force might be electrical or mechanical. ie, for generators, its mechanical and for motors, its electrical. For a linear system, there is a direct relationship between the cause and effect of the vibrations. If the force input doubles, the effective vibration also doubles. Hence if the current flow is high, the noise can be high and vice versa for electrical motors. The amplitude of this mechanical vibrations will be much smaller, compared with the physical dimensions of the body. There will be normal vibrations due to the excitement of the coil of the device and abnormal vibrations due to some faults in the system. Our aim is to distinguish these vibrations and provide the control signal for optimised performance or give warning signals to the system monitoring equipment for the occurrence of the error. These vibrations can be

(i) periodic
(ii) Non periodic
(iii) Harmonic
(iv) Random.

The forced vibrations occur at the excitation frequencies, and it is important to note that these frequencies are arbitrary and therefore independent of the natural frequencies of the system.

The constrained vibrations happen at the excitation frequencies, and it is vital to note that these frequencies are subjective and in this manner free of the natural frequencies of the framework.

The part of mechanical vibration investigation ought to be to utilize mathematical devices for demonstrating and foreseeing potential vibration issues and arrangements, which are generally not clear in preliminary designing outlines. In the event that issues can be anticipated, then outlines can be adjusted to alleviate vibration issues before frameworks are produced. Vibrations can likewise be purposefully acquainted into outlines with exploit advantages of relative mechanical movement and to resound frameworks. Unfortunately, the vibrations in preliminary mechanical plans is infrequently viewed as fundamental, such a large number of vibration studies are completed strictly when frameworks are fabricated. In these cases, vibration issues must be tended to utilizing uninvolved or dynamic outline alterations. Now and again a configuration alteration may be as basic as a thickness change in a vibrating board; added thickness has a tendency to push the instrument work in the ordinary condition.

The concept of damping these vibrations is related to the analysis and modelling of these vibrations. In generally, The data is captured using the motion sensors or vibration sensors firstly ,then it is analysed, and on next, we have to decide what to done for making the system under control. Sometimes it might be a control signal to the controller or some kind of warning pop out in the monitoring system depending up on the characteristics of the vibration. This action is related with the vibration scales, frequency analysis bandwidth and the addition and subtraction of the decibels. The bandwidth of the vibrations is also plays a vital role in the controlling of the system. The controlling through analysis of these signals allows for fault detection and prediction of any anticipated failure, and it has significant benefits including

(i) decreased maintenance costs
(ii) increased availability of machinery
(iii) reduced spare part stock holdings
(iv) improved safety.

Not only the motors and generators, but the HVAC (Heating Ventilation and Air Conditioning) system also posses vibration. It can cause secondary radiation of noise from walls, ducts, floors, etc. A close monitoring of these vibrations also required for the smooth and improved working of the system. Components of the mechanical system (e.g., fans, dampers, diffusers, duct junctions) is also important because it may produce sound by the nature of the airflow through and around them. As a result, almost all HVAC components must be considered. Because sound travels effectively in the same or opposite direction of airflow, downstream and upstream paths are often equally important.

HVAC system is selected as the system to be analysed here. The vibrations are measured using accelerometer sensors and analysis is done on the system the physical system is mathematically modelled and vibration analysis is carried out using MATLAB. The normal parameters considered in an HVAC system are return air flow, chilled water airflow, humidity, real time temperature from the room etc. Here we are analysing the vibration data of the system too. These data are collected from the shaft of blowing motor and the duct of the system.

The failure mode analysis technique is commonly used to identify the faults in the system and where the improvement in machinery is available. Reduction in the maintenance costs can be achieved through the continuous monitoring of the system. And also focuses on the optimisation of the system by achieving specified objectives.

The main problems that faced by HVAC system are given below. They are

1. Low heating/cooling capacity
2. Return air flow stuck
3. Valve leakage
4. Bearing fault of motor

By analyzing the vibration data from the field, it is possible to find what is the current status of the system. For this, we are using mainly two vibrations to the fuzzy controller. One is from the shaft (shaft vibration) and second from duct (duct vibration). The vibration data is then analyzed then. Mean, Standard deviation, Variance, Kurtosis, maximum and minimum peaks and Fourier transform of the data is calculated for the analysis. We can compare these data with a reference data and find out what is the current running status of the system. Optimizing the system is meant by finding the most suitable solution for a problem detected.

A fuzzy set of rules are used in the controller designed. These rules are made on the analysis and studies carried out on the physical system. The system is mathematically modeled and the controller is added on this model. A MATLAB simulation is carried out to find the more optimized output.

As per the above comments, it can understand that the vibration analysis of any system is much important as temperature analysis, current – voltage analysis, metallurgical failure analysis and wear debris analysis. Noise or vibration signal analysis can provide the vital and exact running condition of the machine. But sometimes, the signal, which is to be monitored might be submerged or interfered with other signals. Hence we have to find for an improved method for the analysis of vibration signals.

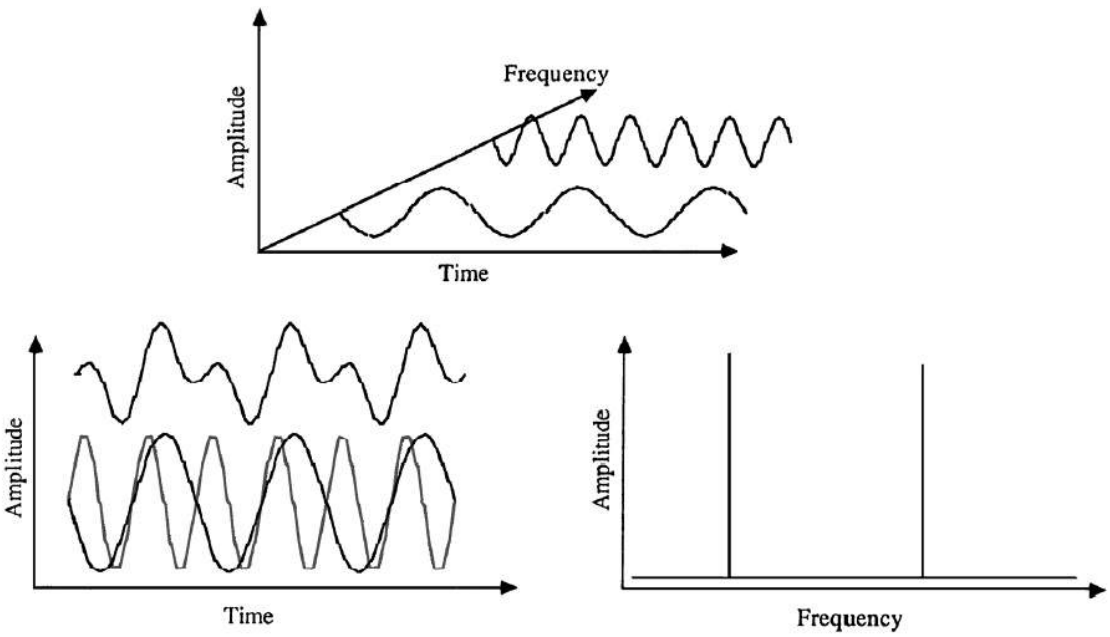


Fig 1.1 Schematic illustration of time and frequency components

The figure 1.1[1] shows the relation between the time and frequency components in general. For making or attaining a control strategy, there is a need to distinguish the vibrations from individual components of the system. In time domain it is not easy to carry out this process. So usually we make use of frequency domain for better results is necessay.

For that, we have to convert these time domain to frequency domain using Fourier transform technique.

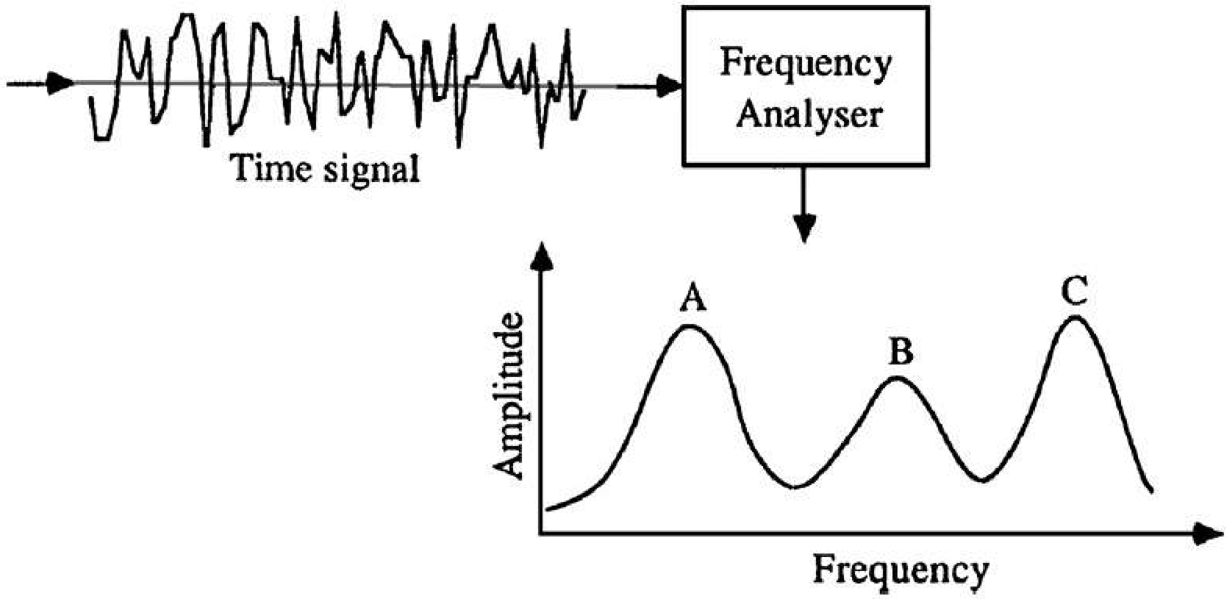


Fig 1.2 Conversion of signal from time domain to frequency domain

It is better to do frequency domain analysis is that we can identify the fault in the system in earlier stage. In time domain, there is a chance of developing the fault before it affect the overall rms vibration level or peak level. So it is better to make use of frequency domain analysis for the optimised result of the system.

A mathematical equivalent model of the physical system is to be simulated using MATLAB. The HVAC system used to study the nature of the vibrations here is of “Al-Wakra hospital” , Wakra-Doha, Qatar. The vibration data was captured from the onsite location of the system . Standard sensors , that are used in industrial environment, are used for the capturing of the data. Here two types of mechanical vibration data are taken for the analysis. They are vibrations from the Shaft of the air blower and the vibration data from the return air duct of the system. A three phase induction motor is used as the air blower for the system. A platinum precision accelerometer is used for the shaft vibrations and a general purpose accelerometer is used for the duct vibration. Platinum precision accelerometer is used because of requirement of high precision data from a sensitive area like motor shaft.

Frequency mode and time mode analysis are made on the vibration data captured from the site. The vibration signals on time mode is of a vast set of data and more convenient way to analyse the data are converting then in to frequency mode. The conversion is done by using FFT algorithm on MATLAB. In addition to the frequency mode analysis, time domain analysis of the same data are also done. The mean, variance, standard deviation, skewness, maximum and minimum peaks , and kurtosis are calculated for an optimistic result. A better result requires a more detailed analysis and studies of the captured data.

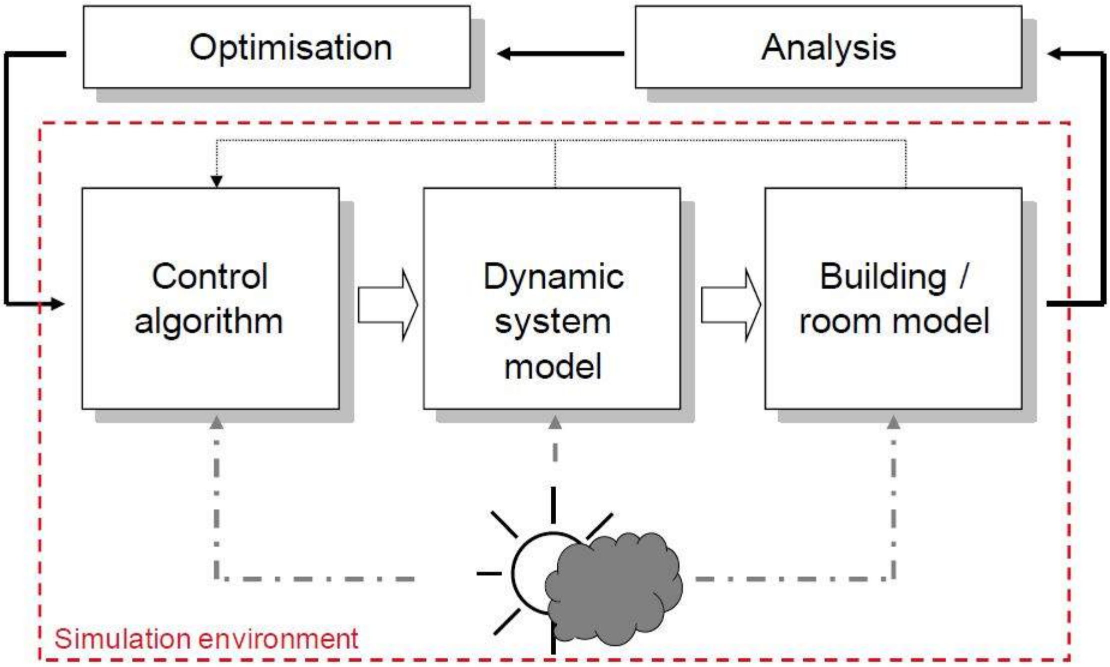


Fig 1.3 The Strategy followed

The figure 1.3 shows the strategy followed in this dissertation work. The vibration signals are analysed in detailed manner. The captured data is used to form the control algorithm of the controller. The dynamic system model is simulated using SIMULINK software. An induction motor drive is modelled here to control the speed of the air blower/induction motor. A speed controller and a direct torque and flux controller is used to drive the induction motor. Here a fuzzy controller is used to control the speed controller output.

The fuzzy controller works on a specific algorithm. This fuzzy set of rules are made by the analysis of the vibration data that captured from the equipment. For a system to be optimized , the problem or error in the system should be identified in a minimum time span and a most suitable solution should be selected. There might be a number of solutions for a single issue. The choice of selecting the exact one is up to controller. The controller decides this by the rule set, which is developed according to the previous data logged from the system. The optimized system should be economical, less energy consuming and fast responding. The system is modelled and simulation tests are done in the SIMULINK.

2. REVIEW OF LITERATURE

2.1 V. Muralidharan , V. Sugumaran, , 2013. Published by Elsevier Ltd.

Vibration based deficiency judgment for mono block divergent pump is mentioned about. Set of these highlights have been removed utilizing diverse wavelets and characterized utilizing fuzzy rationale algorithm (99.84%). From the outcomes and discussions as examined over one can say that highlight extraction utilizing discrete wavelets, rule generation utilizing rough set, and classification through algorithm for grouping are great contender for down to earth utilizations of issue analysis of mono block centrifugal pump. In any case, the outcomes acquired are pertinent for the agent information focuses. For grouping, just trapezoidal membership function is utilized for fuzzy motor as a part of this contextual investigation and different functions might likewise perform similarly well. In the event that we demonstrated that these outcomes are predictable, then they can be considered as a rule for realtime applications.

2.2 Vijay Prakash Pandey and Prashant Kumar Choudhary ISSN 2231-1297, Volume 3, Number 6 (2013), © Research India Publications.

A fuzzy approach is used in this paper to diagnose the current status of induction motor. A fuzzy subset and membership function describing a model of induction motor monitoring system is designed here. The study of different parameters like Magnetic flux, vibration and current flow is considered for the analysis of the problem or current status of the system. The main data diagnosed in this paper is the stator current amplitude. The decision is made as per the condition of the stator current. The vibration data is just referred for the confirmation of the status.

2.3 Vishwanath Hegde, Maruthi.G.S,2011 International Conference on Advances in Energy Engineering (ICAEE).

Usage of MEMS(Micro Electro Mechanial System) technology in condition checking of electrical machines is another thought of identifying the issues in utilizing vibration signals. Air gap eccentricity in induction machine is distinguished carefully and contrasted the outcomes and purported engine current signature investigation utilizing Hall Effect current transducer. The hypothetical results accepted experimentally by both the techniques are introduced and found that eccentricity frequencies ,fecc = (fs ± K fr) around essential can be utilized as a reasonable marker of air gap eccentricity flaws. Further highlights of MEMS, for example, ease, conservative, less power for its operation, light in weight, adaptable in estimation of vibration i.e. a few axis vibration, has drawn the consideration of specialists in adding to a financially good condition checking instrument.

2.4 D.-H. Lee J.H. Lee J.-W. Ahn, Published in IET Electric Power Applications, 20th October 2011.

A servo drive framework with a permanant magnet synchronous motor (PMSM), ball-screw, gear and timing-belt is broadly utilized as a part of industrial applications, for example, numerical control (NC) machine, machine apparatus, robot and processing plant robotization. These frameworks have torsional vibration in the torque transmission from the engine to the mechanical weight owing to the mechanical couplings. This vibration decreases the components of the pace responses and may realize mischief to the mechanical plant. This study give a channel programmed looking of the deafening repeat and data exchange limit from the pace botch with no mechanical sign input to reject the mechanical vibration of the direct feeder framework. The proposed control arrangement can smother the torque request indication of a PMSM in the full repeat domain to reject the mechanical torsional vibration. As the resonating repeat can be moved by the mechanical plans and weight conditions, the channel is planned to interest the vibration repeat commonly and consequently smother the mechanical vibration.

2.5 In Soo Lee, HCI International 2011

A fault diagnosis method for induction motors based on DWT (Discrete Wavelet Transform) and artificial Neural Network is discussed . The proposed algorithm is based on the ART2 NN (adaptive resonance theory 2 neural network) with uneven vigilance parameters. Proposed fault diagnosis method consists of data pre processing part by frequency analysis of vibration signal, and fault classifier for fault isolation by the ART2 NN. Especially, the data pre-processing part which converts the sampled signals into the frequency domain by DWT is very important to improve the performance of the fault diagnosis..

2.6 Chenxing Shenga, Zhixiong Lia, Li Qinb, Zhiwei Guoa, Yuelei Zhanga, CEIS 2011, Open access under CC BY-NC-ND license.

Recent progresses in the area of condition monitoring is done. Detection of mechanical vibrations and fault analysis is very crucial to improve the performance of the system.

To attain to a dynamic system condition monitoring and issue finding, essential errand is the need to get enough dependable trademark information from the system. Because of the variance of the system itself and nature unsettling influence, dependable signal accumulation is genuinely influenced. It is consequently extremely critical for cutting edge signal preparing innovation to dispose of commotion to get genuine signal. Regardless of established or development deficiency determination procedures, they have attained to extraordinary advance in different applications.

2.7 A. Hossain Nezhad Shirazi, H. R. Owji, M. Rafeeyan , The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction, 2011.

Active vibration control of a simply supported rectangular plate made from functionally graded materials (FGM) with fuzzy logic control (FLC) is investigated and compared to the results obtained with the application of PID(Proportional Integral Derivative) control. As per the significance of the vibration diminishment of plates as a real component of industrial and aerospace structures numerous explores in this field have been done. Utilization of smart materials specially, piezoelectric fixes as actuators and sensors can successfully diminish plate vibrations. Firstly differential mathematical statement of movement for a rectangular plate made of FGM outfitted with piezoelectric patches is inferred utilizing a nearby capacity to consider the impacts of piezoelectric mass and stiffness. Classical plate theory is utilized to derive the comparison of movement. Double Fourier series is utilized to acquire the initial nine characteristic frequencies and mode states of plate. Mathematical model analysis is connected to get the framework reactions forced to a beginning condition and a correlation is made between the use of PID control and FLC to hose the plate vibration. The exploration shows FLC has more ability to hose the vibration of the smart plate contrasted with PID control.

2.8 Prof. D E Adams , 2010.

The Fourier series is an important tool for representing excitation and response time histories in analytical vibration analysis. The general idea of Fourier series is to decompose a periodic signal, xd(t), with period T into a sum of simple harmonic signals with various frequencies. Here Fourier series is used to decompose a nonperiodic signal into harmonics over a given time interval, T. The decomposition is given below for real and complex number notations.

The conversion of time domain to frequency domain of the data and various analysing strategies used for the interpretation of the fault. Non linear signals needs another kind of strategy to study the characteristics.

2.9 ASHRAE, 2009.

The vibration analysis in HVAC system and its control strategies. It gives the detailed system analysis for noise control. It explains how the source of the sound is called the noise-generating mechanism. The sound travels from the source via a path, which can be through the air (airborne) or through the structure (structure borne), or a combination of both paths, until it reaches the receiver (building occupant or outdoor neighbour) and proper studies have explained.

2.10 B. P. Dubey, S.D. Dhodapkar and R.K. Patil, 2008

A software package, named ViSFoTA, has been developed for analysing vibration signal using Fourier Transformation and Artificial Neural Network (ANN). The package has been developed primarily for applications in seismology. It can also be used to perform analysis of time series generated by any vibration signals in different frequency bands. The package consists of two major parts – the pre-processor for the vibration signal and the ANN module.

2.11 M. Ning , M. Zaheeruddin , Z. Chen , IEEE, 2006.

A fuzzy based uncertainty analysis method is employed here. Uncertain parameters like random vibration from motor, duct and casing are studied and the data is analysed for the optimized working of the HVAC system. Other major factors considered are zone temperature, discharge air temperature, humidity, temperature of chilled water and condenser water. From the analysis of data from site, a fuzzy controller is designed. It would make the system more stable, if a disturbance applied to it. From this paper, the idea of using the vibration data on a controller is explained. Extended transformation approach is used to find the logical solution of the problem.

2.12 Serdar HÜGÜL ,Dokuz Eylül university graduate school of natural and applied sciences (2005)

The finite element method and numerical time integration method (Newmark method) are employed in the vibration analysis. The impact of the rate of the moving load on the element amplification variable which is characterized as the proportion of the most extreme element removal at the relating hub in the time history to the static relocation when the load is at the mid – purpose of the structure is researched. The impact of the spring stiffness joined to the casing at the conjunction purposes of bar and segments are likewise assessed. PC codes written in Matlab are created to compute the element reactions. Dynamic reactions of the building structures and basic load speeds can be found with high precision by utilizing the limited component strategy

2.13 P. Riederer, Ninth International IBPSA Conference Montréal, 2005.

In this paper, the mathematical model of the physical system is simulated in MATLAB/SIMULINK. It gives a synthesis of HVAC on the use of simulation software. The control strategy and monitoring system of HVAC system is modelled here. This paper was helpful for the designing of the controller. The paper deals with many parameters of the system such as energy conception, airflow and hydraulic studies, contro strategies, sizing problem, etc. the real controllers are being tested in the virtual system here. The results were gathered for a more stable and optimized working of the system. Modelling and simulation of physical phenomena is explained. The commissioning, fault detection and diagnosis of the HVAC system is done here and coupling with outside of the tool box are also done in this paper.

2.14 T. I. Salsbury, R. C. Diamond , IEEE, 2004.

In HVAC system, normally a PID controller is employed to control the action. In this paper, the authors compares the typical PID controller with a model based feed forward controller. The system in modelled mathematically and a feed forward system is designed to detect errors and control the process. This paper is helpful to understand the scope of fuzzy controller as feed forward controller. It makes the system more stable and consistent to disturbance. BACnet communication protocol is used here for the communication of controller with the field devices.

2.15 Norton M.P., Karczub D.G. ,(CUP, 2003)

Some of the more important fundamental considerations required for a systematic approach to engineering noise and vibration analysis and control, the main emphasis being the industrial environment. The main difference is the emphasis on the wave–mode duality, and the reader is encouraged to think in terms of both waves and modes of vibration. As such, the introductory comments relate to both lumped parameter models and continuous system models. The sections on the dynamics of a single oscillator, forced vibrations with random excitation and multiple oscillator are presented using the traditional ‘mechanical vibrations’ approach. The section on continuous systems utilises both the traditional ‘mechanical vibrations’ approach and the wave impedance approach. Magnitude and time domain signal analysis techniques, frequency domain signal analysis techniques, sound intensity analysis techniques, and other advanced signal analysis techniques are described. A review of design concepts for a plant-wide condition monitoring system integrating performance monitoring, safety monitoring, and on-line and off-line condition monitoring of electrical devices are also there for the improved performance and optimization of the system.

2.16 Satomi Hattori, Muneaki Ishida and Takamasa Hori , Trans. of the Society of Instrument and Control Engineers ,(2002).

A suppression control method of vibration for brushless DC motor utilizing feed forward compensation control, and a generation method of compensating signals for the feed forward control by repetitive control with Fourier transform utilizing a vibration signal acquired by an acceleration sensor attached to the motor frame. Because the vibration signals detected by the acceleration sensor contain various complicated frequency components due to motor torque vibrations and mechanical resonant vibrations around the motor load system, stabilisation will be less for the repetitive control system. A generation method of the compensating signals of the repetitive controller considering the periodicity of motor torque ripples, and using Fourier transformer which can select particular frequency components. In order to realize on-line generation of feed forward compensating signals to reduce the vibration, auto-tuning method of the repetitive control parameters is also presented.

2.17 Tom Irvine, Sample Rate Criteria and the Nyquist Rule (2000)

Various transducers such as accelerometers and analysers are described. The methods to change these time domain signals to frequency domain signals are also explained. The analysis of the signal will be more accurate if the sampling rate is high. Analysis will be more accurate if we did a frequency mode analysis. The Fourier transform technique and shock response spectrum are used to analyse the sampled data.

2.18 Ian Howard , Acoustics Australia technical magazine (1995)

The advent of higher level interpretive based signal processing software products like MATLAB has added a new dimension to vibration signal processing method. Here the application of MATLAB to analysis of the vibration from rotating machinery such as rotors, gears and bearings are explained with MATLAB simulations. Sophisticated signal processing techniques can be developed within a very short period of time given and the flexibility and interactive nature of MATLAB and the range of in-built functions such as Fourier transforms, cubic interpolations and digital filters are also discussed.

3 SCOPE OF THE STUDY

The scope of the vibration signal analysis and modelling is very important as it plays a very important role in improving the performance of any electrical devices. Various AC motors are used in industrial applications, because of simple structure, easy to use and less maintenance purposes. These AC motors should be monitored continuously for a high end production level of the plant. The following figure 3.1 [20] shows fuzzy controller on a induction motor.

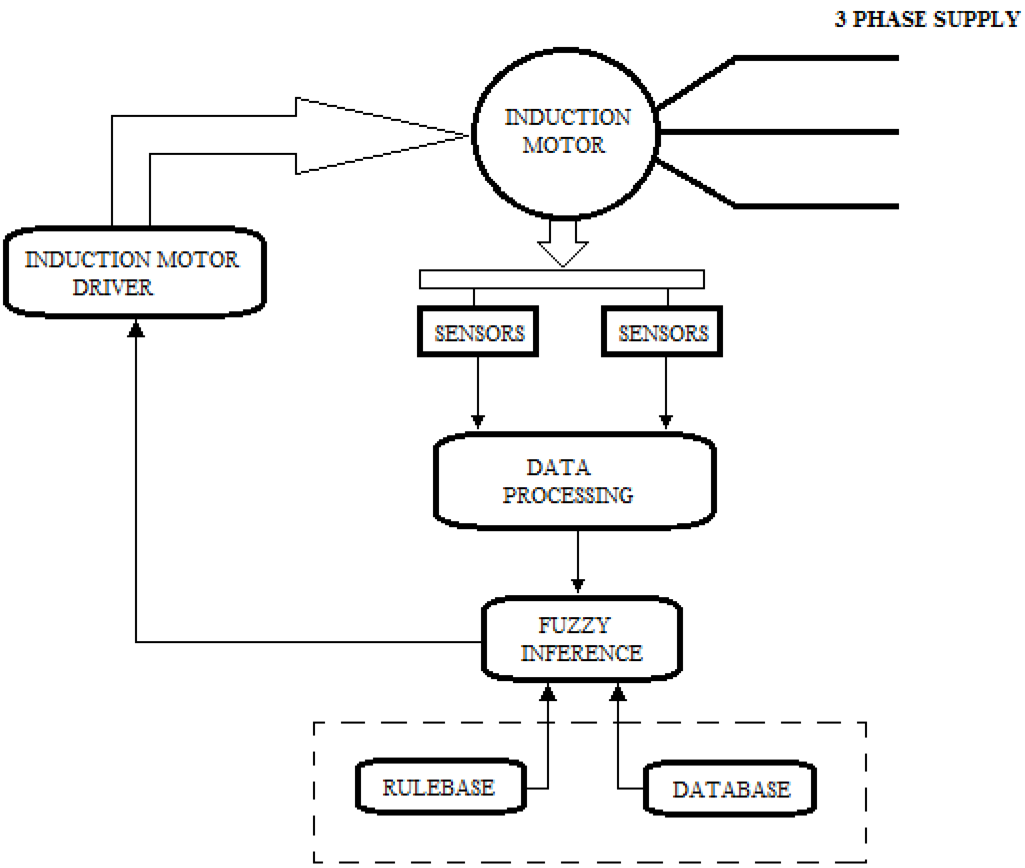


Fig 3.1 Schematic diagram of speed driver using fuzzy controller on induction motor

The control strategy include various stages.

- Detection of system mechanical vibration
- Extraction of specific component by Fourier transform

- Analysis of this FFT signal using repetitive control algorithm
- Generation of control signal from the controller
- Comparison of control signal with the required parameter
- Final control element or actuator to control the equipment at the last stage.

The real life applications of vibration signal analysis are too much as it is very simple to execute, easy to understand and almost zero maintenance equipments. The components used for this purpose are very compact. The analysis is applicable for almost all electrical devices, to which we give or take electrical power as input or output. The mechanical vibration of these devices are monitored for not only fault detection but also optimised performance of the system. If the vibration magnitude and bandwidths are under the pre set range , only optimisation techniques are employed. Such as voltage or current control, frequency control, etc. but if the vibration is out of the specific band or value, then these is a fault occurred internally or externally. This might be electrical or mechanical. The vibration signals are captured and analysed for these types of emergencies and analyser sends a control signal to the controller as per the requirement.

4 OBJECTIVE OF THE STUDY

4.1 Measurement of vibration on equipment.

Examination of equipment vibration generated by system components, such as bearings, drives, pumps, etc. Measurement of the natural frequencies (resonances) of vibrating equipment or connected structure(s) examination of equipment installation factors, such as equipment alignment, vibration isolator placement, etc and measurement of the unbalance of reciprocating or rotating equipment components gives the idea about what action to be done to avoid that fault.

4.2 Determining the problem source

Determining the problem source is very important as to produce a control signal, according to the fault. Various methods are used to carry out this process, such as Fourier transform analysis, filtering methods, Fuzzy logic system, Artificial Neural Network, Wavelet analysis, etc. It should be noted that if the problem source is not determined, then optimisation of the system is not attained. ie, if the problem is from rotor section of an induction motor, then the vibrations will be in a range such that we will be able to find that the abnormality is in the rotor area. The same is applicable if a fault occurred there in any of mechanical part. Identification of problem source is very important for a fast time reaction to the problem.

4.3 Determining problem type

Once the source is identified, then next is to find the characteristics of the noise and have to reach in to a point that what type of interference is occurred. Some of the normal problems showed by the machines are given below.

4.16.1 Equipment improperly specified or installed, poorly balanced, misaligned, or operating outside of design conditions

4.16.2 Equipment with inadequate or improper vibration isolation

4.16.3 Resonances in equipment, vibration isolation system

4.16.4 High/low rated voltage/current inflow to the equipment

4.16.5 Faults in any mechanical body part of the system

4.4 Taking action to the determined problem

The signals captured by sensors are given to controllers. Here general purpose accelerometer vibration sensor are used. These signals are analyzed using Fourier transform. An appropriate control signal or warning signal is generated according to the problem detected. This may be to the controller or to the monitoring system for recording. if the found out problem is something that cannot handle by the controller, i.e. requirement of any mechanical body replacement etc. the warning signal is send to the monitoring system.

4.5 Continuous monitoring

Continuous monitoring of the system is required to make sure whether the analysis were correct or not for monitoring. It is very important to to the continuous evaluation of the parameters to make the quality assurance . Feedback control strategy is employed in monitoring the system to make the system accurate. The performance is continuously monitored and signals or pop outs are send to the controller in case of any abnormality is detected.

5 RESEARCH METHEDOLOGY

5.1 VIBRATION MEASUREMENT

The advent of low-cost vibration measurement systems has made detailed vibration evaluation much more practical. Any steady-state vibration frequency spectrum, such as that generated by a machine operating at a fixed speed and operating condition, can be expressed as either acceleration,, velocity, or displacement. A simple relationship makes it possible to easily convert each of these quantities to the others. The relation between each is given below

$$V=\frac{d}{dt}(D) \quad \text{(eqn 5.1.1)}$$

$$A=\frac{d}{dt}(V) \quad \text{(eqn 5.1.2)}$$

; Where

D - Displacement

V - Velocity

A - Acceleration

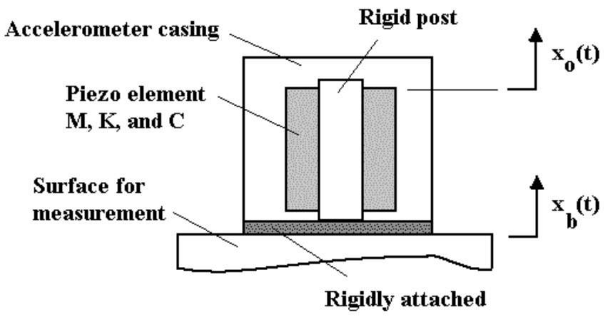
Vibration measurements must specify how the amplitudes are expressed. These can be either peak (the maximum level), peak-to-peak (the range between minima and maxima), or rms (root mean square). Several factors must be considered when making vibration measurements such as reference signal, frequency range of measured signal, transducer to be used, etc. An extremely rigid attachment method is used for tranducers, such as dental cement, or a screwed connection with oil between the surfaces, is required for accurate measurement at very high frequency (about 5 kHz). Epoxies or other high-quality glues tend to be somewhat more limited but are acceptable in nearly all situations. Using magnetic attachments, though convenient and fully acceptable in many cases, limits the upper frequency range of accurate data (typically about 150 Hz). Another common but frequency-limited method of attachment is wax, in which an external waxing is done over the mechanical part along with the sensor. It is essential to validate that the attachment between sensor and vibrating part in a given application is capable of measuring vibration to the needed degree of accuracy.

Vibration monitoring and analysis is very much depended up on the machine mounted sensor, as any wrong data can mislead to taking improper actions. Three parameters representing motion detected by vibration monitors are displacement, velocity, and acceleration. These parameters are mathematically related and can be derived from a variety of motion sensors as per equation 5.1.1 and equation 5.1.2. Selection of a sensor proportional to displacement, velocity or acceleration depends on the frequencies of interest and the signal levels involved. Sensor selection and installation is often the determining factor in accurate diagnoses of machinery condition.

Some of the vibration measurement devices are following-

5.1.1 Transducer

It gives output electrical signal, proportional to the vibrations present in the body. It is defined as a device that converts variations in a physical quantity, such as pressure or brightness, into an electrical signal, or vice versa. The most commonly used transducer called accelerometer measures vibratory acceleration and sends to the controller. They are compact, relatively rugged, capable of a wide measurement range in terms of both vibration level and frequency, and are easy to install. It is important to note that many transducers, including all accelerometers, cannot measure vibration below a minimum frequency associated with the transducer. The frequency range of transducers varies with the models and types used. The practical implication of that limitation is that, in many cases, measured acceleration cannot be fully converted to displacement, and can never be used to quantify static displacement. For that reason, in cases where very-low-frequency vibration measurements are required, special transducers, such as displacement probes, are needed.



$$x_0(t) - x_b(t) \sim \ddot{x}_b(t)$$

Fig 5.1 Schematic of single degree-of-freedom shear mode piezoelectric accelerometer

In the figure, there are piezo electric elements M,K and C are moulded inside accelerometer casing. And the whole instrument is rigidly attached to the surface on which vibration measurement is to be done. If $X_0(t)$ is the initial position and

$X_b(t)$ is the final position to the instrument, then the electric signal is send from transducer , proportional to $\ddot{X}_b(t)$, where

$$\ddot{X}_b(t) = X_0(t) - X_b(t) \quad \text{(eqn 5.1.3)}$$

5.1.2 Pre amplifier

A preamplifier for the transducer, which amplifies the signal to a level suitable to the data acquisition system. Preamplifier amplifies the output signal from the transducer and it is fed to the controller. It improves the quality of the signal to the controller and lead to a better performance.

5.1.3 Analyzer

The most basic analyzers measure the overall vibration amplitude across a specified frequency range. This frequency range depends up on the possible faults that can occur on the system. The type of analyser to be used depends up on the frequency range of the reference signals. It shows the vibration level on its LCD display. Many are capable of measuring vibration as a function of frequency, with constant frequency spacing. These so-called ―narrowband, or fast Fourier transform (FFT), analyzers display the vibration frequency spectrum with a very high degree of resolution, typically at hundreds or even thousands of frequencies. Alternative analyzers of the constant-percentage bandwidth type measure the vibration spectrum across a relatively small number of frequency bands, the widths of which increase proportionally to the centre frequency of each band.

The data is given to FFT should be in the proper frequency range. It is achieve by assigning suitable analysers. This significantly affects the spectral data toshow they are affected. Among them are the window type , the number of averages, the window overlap, the frequency resolution , and the maximum frequency.

Typical application of vibration measurements includes comparison of overall vibration levels (the total across a defined frequency range) with general guidelines representing typical levels to be expected from various classes of machinery. This most basic measurement is often used in connection with routine machinery maintenance or monitoring. Using a narrow band measurement system, we used to measure determination of exact frequencies of tonal vibration sources. This information can be critical in identifying the specific machine or vibration component responsible for excessive vibration or noise. In some cases, a high degree of measurement resolution is required to separate closely spaced tones. For example, in 60 Hz applications, twice the motor or compressor running speeds are typically close to 118 Hz, while twice the electrical line frequency is 120 Hz. Clearly, while the difference between these frequencies is inaudible, knowing which source is responsible for a problem is essential to developing a solution.

5.2 VIBRATION SIGNAL ANALYSIS

The mechanical vibrations thus obtained is of time domain for analysis. To convert them in to frequency domain to determine the fault. This can be done by Fast Fourier Transform method or some other suitable methods. Forces and responses in real world systems are we need to understand how to express them in analytical terms. Here the focus is on deterministic analytical forced vibration response analysis: Assume that the excitation or force exactly at any moment in time is known. In random vibration analysis, we can only describe the statistical properties of the excitation, which is not a continuous sample of data. The data is randomly collected and analysed on this method.

An excitation (or response) is said to be harmonic when it contains a single frequency component. A simple harmonic signal is a constant amplitude harmonic. Simple harmonic signals are the simplest kind of periodic signals, which repeat themselves every T seconds. For instance, a linear vibrating system exhibits a simple harmonic free response to a general set of initial conditions:

$$M\ddot{x}_d + Kx_d = 0$$
$$\text{for } x_d(t) = A\cos(\omega_n t + \varphi)$$

(eqn 5.2.1)

The quantity ωnt+φ is called the instantaneous phase angle of the signal, xd(t), and φ is called the initial phase angle. The velocity and acceleration of this system are at +90 and +180 degrees, respectively, with respect to the displacement:

$$
\begin{aligned}
&x_d(t) = A\cos(\omega_n t + \varphi) \\
&\dot{x}_d(t) = -A\omega_n \sin(\omega_n t + \varphi) = A\omega_n \cos\left(\omega_n t + \varphi + \frac{\pi}{2}\right) \\
&\ddot{x}_d(t) = -A\omega_n^2 \cos(\omega_n t + \varphi) = A\omega_n^2 \cos(\omega_n t + \varphi + \pi) \\
&\text{so } \ddot{x}_d = -\omega_n^2 x_d
\end{aligned}
$$

(eqn 5.2.2)

Thus, acceleration is proportional to displacement for simple harmonic motion. We can also use complex numbers that rotate in the complex plane (phasors) and Euler's formula to describe harmonic signals. For instance, xd(t) from the equation above can be rewritten as follows:

$$
\begin{aligned}
x_d(t) &= A\cos(\omega_n t + \varphi) = \\
&= \mathrm{Re}\left[Ae^{j(\omega_n t+\varphi)}\right] = \mathrm{Re}\left[A\angle\omega_n t + \varphi\right] \\
&= \frac{Ae^{j(\omega_n t+\varphi)} + Ae^{-j(\omega_n t+\varphi)}}{2}
\end{aligned}
$$

(eqn 5.2.3)

and then the 90 degree phase difference between the displacement-velocity and velocity-acceleration is accounted for with a factor of jωn, which introduces a +90 degree rotation in the complex plane:

$$
\begin{aligned}
x_d(t) &= \mathrm{Re}\left[Ae^{j(\omega_n t+\varphi)}\right] \\
\dot{x}_d(t) &= \mathrm{Re}\left[(j\omega_n)^1 Ae^{j(\omega_n t+\varphi)}\right] \\
\ddot{x}_d(t) &= \mathrm{Re}\left[(j\omega_n)^2 Ae^{j(\omega_n t+\varphi)}\right]
\end{aligned}
$$

(eqn 5.2.4)

We will develop this idea of using complex numbers to describe two different characteristics in a signal, magnitude and phase (A and ωnt+φ). The period of oscillation in seconds, T, is inversely proportional to the circular frequency, ω, in radians/second according to ω=2π/T. The frequency, f, in Hertz (cycles/second) is the inverse of the period of oscillation, f=1/T. When two simple harmonic signals with slightly different frequencies are added, the following result is obtained using trigonometry:

$$
\begin{aligned}
x_1(t) + x_2(t) &= A\sin(\omega t) + A\sin(\omega t + \Delta\omega t) \\
&= A[\sin(\omega t) + \sin(\omega t + \Delta\omega t)] \\
&= A\left[2\sin\left(\frac{\omega t + \omega t + \Delta\omega t}{2}\right)\cos\left(\frac{\omega t - \omega t - \Delta\omega t}{2}\right)\right] \\
&= 2A\cos\left(\frac{\Delta\omega t}{2}\right)\sin\left(\omega t + \frac{\Delta\omega t}{2}\right)
\end{aligned}
$$

(eqn 5.2.5)

which exhibits the so-called beating phenomenon. The amplitude slowly varies from 0 to 2A (where A is constant) according to the small frequency, $\Delta\omega/2$, as the signal frequency remains constant at the larger value $\omega+\Delta\omega/2$.

The Fourier series is an important tool for representing excitation and response time histories in analytical vibration analysis. The general idea of Fourier series is to decompose a periodic signal, xd(t), with period T into a sum of simple harmonic signals with various frequencies. We can also use Fourier series to decompose an aperiodic signal into harmonics over a given time interval, T. The decomposition is given below for real and complex number notations. The response to each term in this series is calculated independently from all the others and then the results are added as shown in Figure 5.1

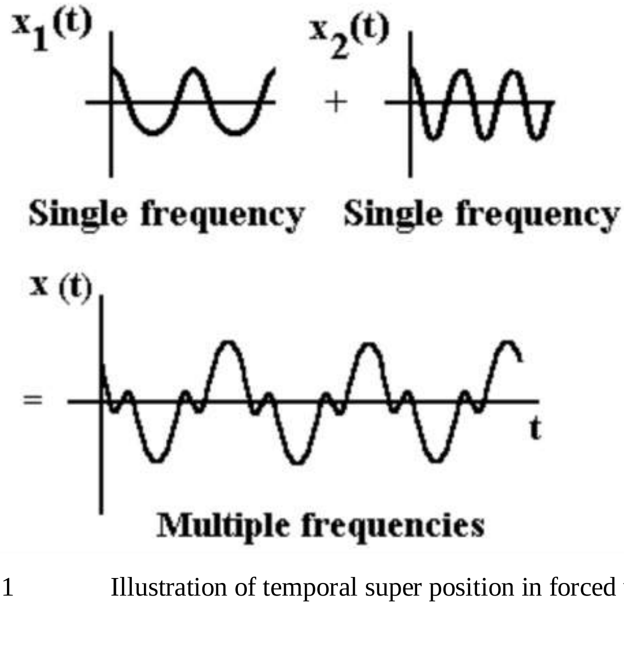


Fig 5.2.1 Illustration of temporal super position in forced vibrations

$$x_d(t) = \sum_{n=0}^{\infty}\left[a_n \cos(n\omega_o t) + b_n \sin(n\omega_o t)\right]$$

$$\text{where } a_n = \frac{2}{T}\int_{-T/2}^{T/2} x_d(t)\cos(n\omega_o t)dt$$

$$b_n = \frac{2}{T}\int_{-T/2}^{T/2} x_d(t)\sin(n\omega_o t)dt \text{ with } T = \frac{2\pi}{\omega_o}$$

$$x_d(t) = \sum_{n=-\infty}^{\infty} c_n e^{jnw_0 t}$$

$$\text{where } c_n = \frac{1}{T}\int_{-T/2}^{T/2} x_d(t)e^{jn\omega_o t}dt \text{ with } c_n = \frac{a_n}{2} - j\frac{b_n}{2} \text{ and } c_{-n} = c_n^* = \frac{a_n}{2} + j\frac{b_n}{2}$$

(eqn 2.5.6)

By decomposing the vibration signals into separate harmonics as in equation (2.5.6), The study can be made by multiple inputs. Using this formula, Solutions for the problems like interfering of signals and merging of unwanted noices to the vibration signals can also be find out. Linear superposition is what enables us to analyze the forced response of vibrating systems in this way. Superposition holds because stable linear vibrating systems only respond at the excitation frequency in the steady state. Among other things, this guarantees that the response to each harmonic is independent from the response to all other harmonics (see Figure 4.2). In nonlinear systems, two individual response harmonics often conspire to create new harmonic response components, which cannot be explained with linear models. The analysis is primarily limited to stable linear vibration in which systems only respond at the excitation frequency in the steady state.

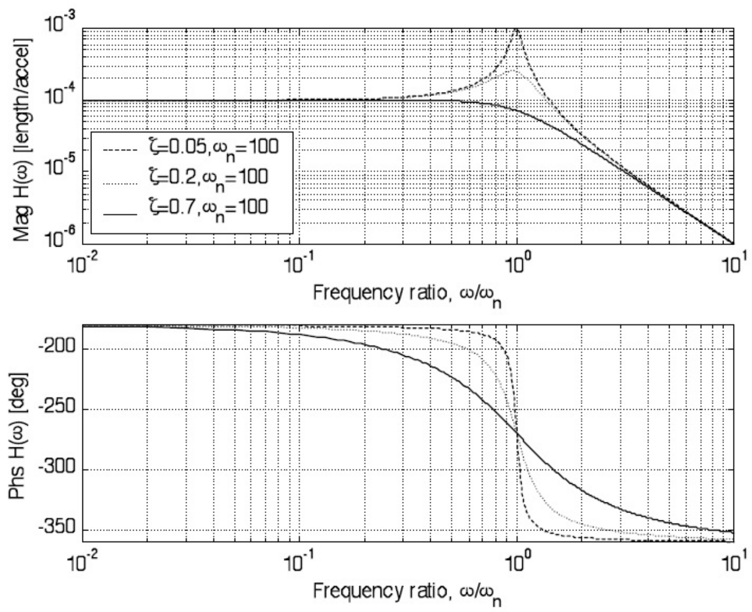


Fig 5.2.2 Frequency response magnitude and phase characteristics of an accelerometer

Various methods are used for the analysis of these vibration signals practically. Some of them are explained below.

5.2.1 FAST FOURIER TRANSFORM

A periodic function can be represented as a sum of infinite number of (co-)sinusoidal components at equally spaced frequencies with the interval of 1/T, where T is the period of the function, the so called Fourier Series.[4]

FREQUENCY SPECTRUM

At the point when harmonic segments of a signal are known, the signal can be introduced in an alternate manner that highlights its frequency content instead of the ideal time domain content. Presenting the third hub of frequency opposite to the sufficiency time plane the harmonic parts can be plotted in the plane that compares to their frequencies. Figure 5.2.3 shows the frequency spectrum of a random signal.

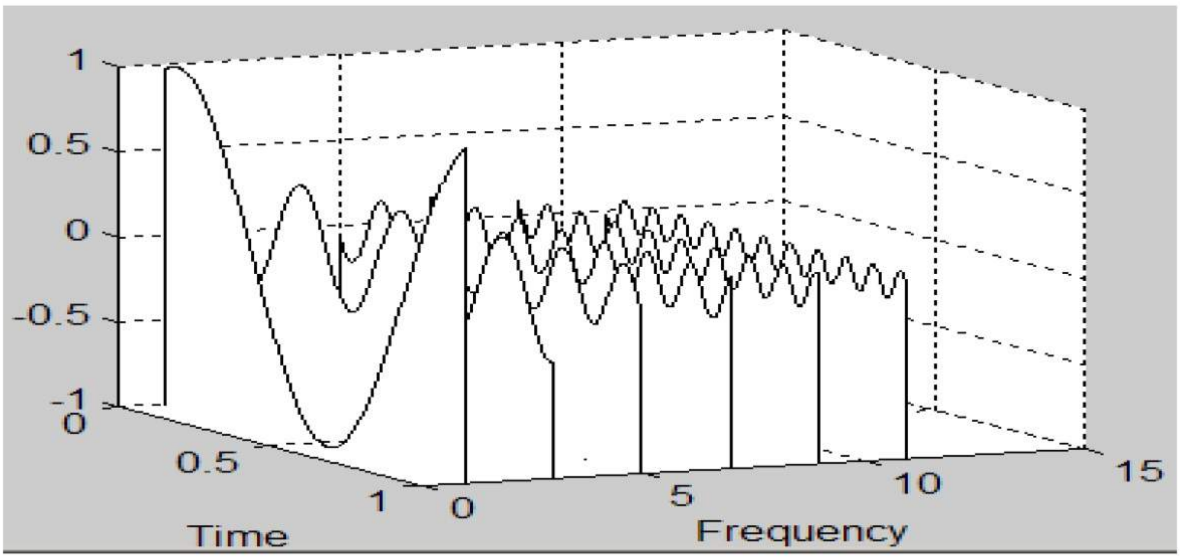


Fig 5.2.3 Time-Frequency-Amplitude representation of a random signal

The purpose of frequency analysis is to devise a method to extract an estimate of frequency components which are not known a priori. The process is known as the Discrete Fourier Transform (DFT)[4].

FOURIER TRANSFORM

So as to concentrate one of these vectors, one needs to make it stationary, numerically talking, for the span of perception and after that integrate over the season of perception. Multiplying a vector

$$e^{j(\omega t+\phi)}$$

which rotates with frequency ω, by

$$e^{-j\omega t}$$

produces a vector with the ωt eliminated, i.e. stationary vector:

$$e^{j(\omega t+\phi)}\,e^{-j\omega t}=e^{j\phi} \quad \text{(eqn 5.2.7)}$$

Vectors with different frequencies keep on turning and their integration (or summation) will be near to zero.

It is now clear that the continuous Fourier Transform of signal g(t), which extracts its component G at the frequency ω, is defined as

$$G(\omega)=\int_{-\infty}^{+\infty} g(t)\,e^{-j\omega t}\,dt \quad \text{(eqn 5.2.8)}$$

The equation is impractical and for a signal sampled at discrete times tn and over the finite duration kΔt, the so called Discrete Fourier Transform (DFT) is used

$$G(\omega)\approx\sum_{n=1}^{k} g(t_n)\,e^{-j\omega t_n} \quad \text{(eqn 5.2.9)}$$

In practice, the circular frequency f in Hz is used instead of ω in rad/s. For such a case

$$G(f)\approx\sum_{n=1}^{k} g(t_n)\,e^{-j2\pi f t_n} \quad \text{(eqn 5.2.10)}$$

These Fourier Transform equations must be applied to both the positive and the negative frequency.

FAST FOURIER TRANSFORM (FFT)

The Fast Fourier Transform (FFT) is an algorithm for calculation of the DFT first published in 1965 by J.W.Cooley and J.W.Tuckey. It has revolutionised the modern experimental mechanics, signal and system analysis, acoustics, and paved the way for the introduction of modal analysis. The FFT algorithm applies only to signals comprising a number of elements which is equal to 2^m (e.g. $2^8 = 256$, $2^{10}=1024$ etc.).

Its main advantage is that it significantly reduces the computation time by a factor of the order m/log2m , i.e. more than 100 times for a sample of 1024 elements. From the earlier discussion it is clear that the FFT should return a set of complex numbers, with exception of the spectral components at f=0 and f=fs/2 (the Nyquist frequency), which are both real.

The number of FFT elements is equal to the size of the time sample. The second half of these complex numbers corresponds to negative frequencies and contains complete conjugates of the first half for the positive frequencies, and does not carry any new information.

Implementations of FFT algorithm are commonly available:

- In MS Excel® the Fourier Analysis can be found under Tools->Data Analysis.
- In Matlab® there is a function fft()

The following figure 5.2.4 shows algorithm of finding FFT for any mechanical vibration signal obtained from any transducer.

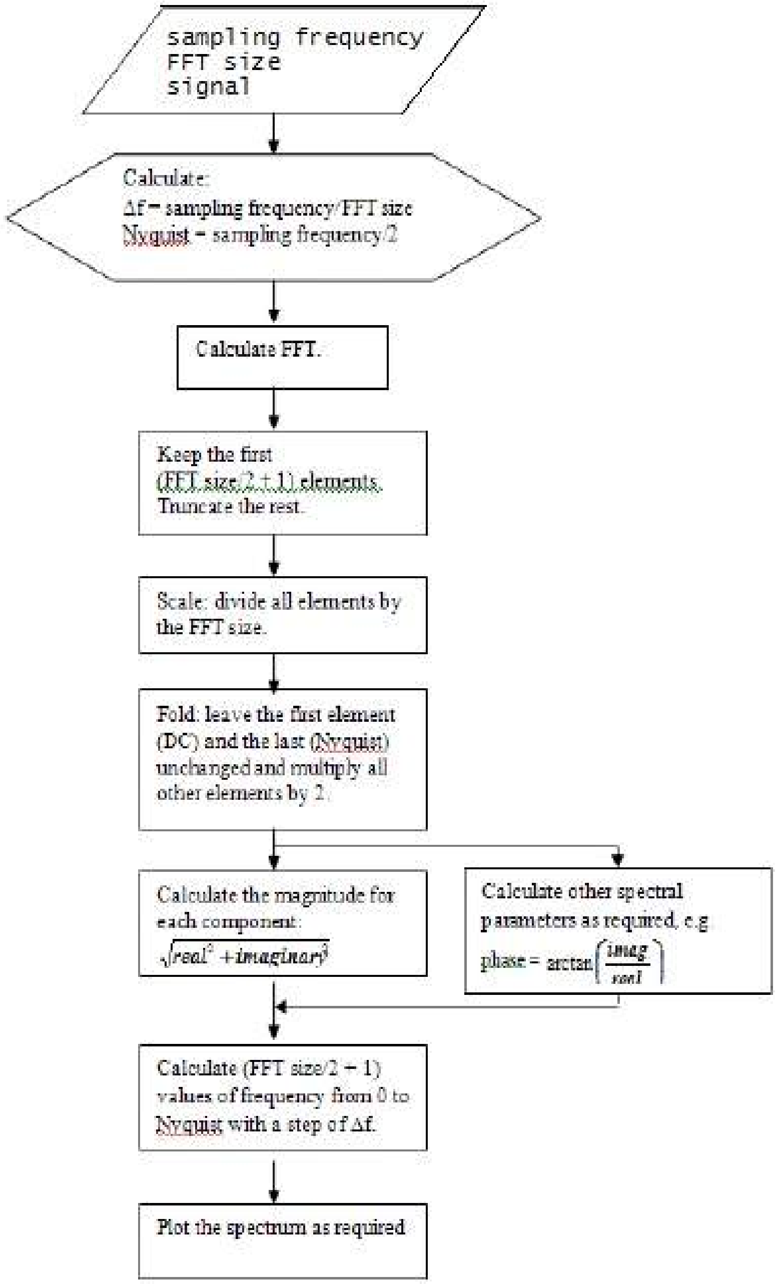


Fig 5.2.4 Algorithm for folding the FFT spectrum and producing a magnitude spectrum

In MATLAB , the FFT of a time varying signal is directly obtained. This data are used for the analysis of the signal. The fuzzy rule sets are made on these analysis results.

5.2.2 Mean

Finding the mean value after a specified set of vibration data from sample and comparing it with the reference data will help us to define the error type and the magnitude of the fault. The optimized output can be find out by analyzing the change in mean of the vibration data.

$$Mean = \frac{(Peak\ value - Crust\ value)}{2}$$

5.2.3 Variance

The variance for a sample set of data means how far the samples are spread out over the entire range. It gives the amount of chance of any error to be occurred in the machine. Variance of vibrations from a motor near to zero indicates that it is working in good condition. Analysis on the vibrational data on its variance gives us the probabilty of running the instrument on good condition.

$$\mu = \int xP(x)dx$$

And x is the sample in data

P(x) is the probabilistic function.

5.2.4 Standard deviation

The standard deviation of the sampled vibration data over a time period gives the quantity of the error occurred in the field. It is defined as the closeness to the mean value of specific set of sample data.

$$\sigma = \sqrt{\int (x-\mu)^2 p(x)dx}$$

Where

$$\mu = \int xP(x)dx$$

And x is the sample in data

P(x) is the probabilistic function.

5.2.5 Kurtosis

Kurtosis is the measure of peak of the probabilistic function for a particular arrangement of inspected information. One normal measure of kurtosis is in light of a scaled adaptation of the fourth snippet of the information or population, however it has been contended that this truly measures overwhelming tails. By and large a higher kurtosis shows a high variance in the vibration signal information and henceforth an issue is recognized over the field. A high kurtosis conveyance has a more honed crest and fatter tails which is implied as mistake, while a low kurtosis dissemination has a more adjusted top and more slender tails prompting the suspicion of smooth running of the machine.

5.2.6 Skewness

Skewness is a measure of the asymmetry of the probability distribution for a genuine esteemed arbitrary variable about its mean. The skewness worth can be positive or negative, or even unclear. The subjective understanding of the skew is muddled. Positive skew demonstrates that the tail on the right side is longer or fatter than the left side. In situations where one tail is long however the other tail is fat, skewness does not comply with a basic rule. Case in point, a zero quality shows that the tails on both sides of the mean offset, which is the situation both for a symmetric distribution, and for unbalanced distributions where the asymmetries level out, for example, one tail being long however thin, and the other being short yet fat. Further, in multimodal distributions and discrete distributions, skewness is likewise hard to decipher. Imperatively, the skewness does not focus the relationship of mean and middle.

5.2.7 Fuzzy Logic Control

A fuzzy concept is a concept of which the boundaries or range of application can vary considerably according to context or conditions, instead of being fixed once and for all. Here we make use of this technique for analysing the vibration signals. On this method undergo a predefined algorithm and finds solution for the problem. The step by step procedure to be followed in sequence is presented in Fig. 5.2.7. First, the vibration data is acquired from the experimental setup using DAQ system. The features are then extracted using Discrete Wavelet Transforms (DWTs). Then, set of rules is framed using rough set and fed as an input to the fuzzy inference engine. Finally, the classification accuracy is achieved by means of confusion matrix there by the faults are segregated.

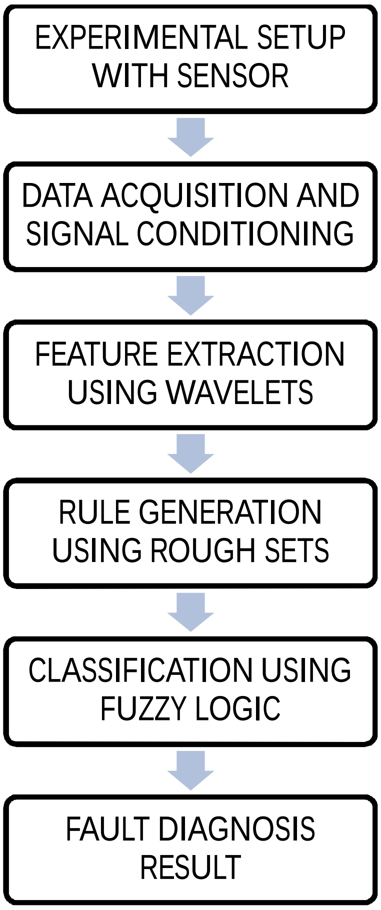


Fig 5.2.5 Flow chart of HVAC fault diagnosis system.

The primary objective of this work is to find whether the induction motor is in good condition or in faulty condition. This is done by looking at the current status of the framework with references utilizing if-then algorithm. If the pump is found to be in faulty condition, then it has to be segregated into cavitation, bearing fault, impeller fault, and both bearing, impeller fault together. This study focuses on the use of rough set theory for fault diagnosis of induction motor.

5.2.7.1 Fuzzy classifier

Fuzzy logic discovers applications in variety of spaces. It is turned out to be much cheaper, stronger and dependable than the greater part of the classification algorithms. Specifically, fuzzy logic is most utilized when the information data is not fresh in nature and it gives ambiguous data. For the issue under study, the faulty vibration with bearing and impeller won't happen abruptly, it comes progressively. All things considered, there is no threshold quality (fresh data) in view of which the choice on the state of the bearing, impeller—whether bearing or impeller is presently great or faulty—can be taken. The issues of this kind can be demonstrated utilizing fluffy classifier all the more nearly. The purpose of Fuzzy logic is to guide the data space to yield space with the assistance of set of "if–then" proclamations called rules. The guidelines which were determined utilizing rough-set algorithm are the inputs to fabricate a fuzzy inference motor utilizing membership function

There are five possible outcomes namely normal, reduced capacity, air stuck, valve leakage and bearing fault. They indicates the conditions of the system as per their names. Fig. 5.2.6 shows the triangular membership function for the outputs.

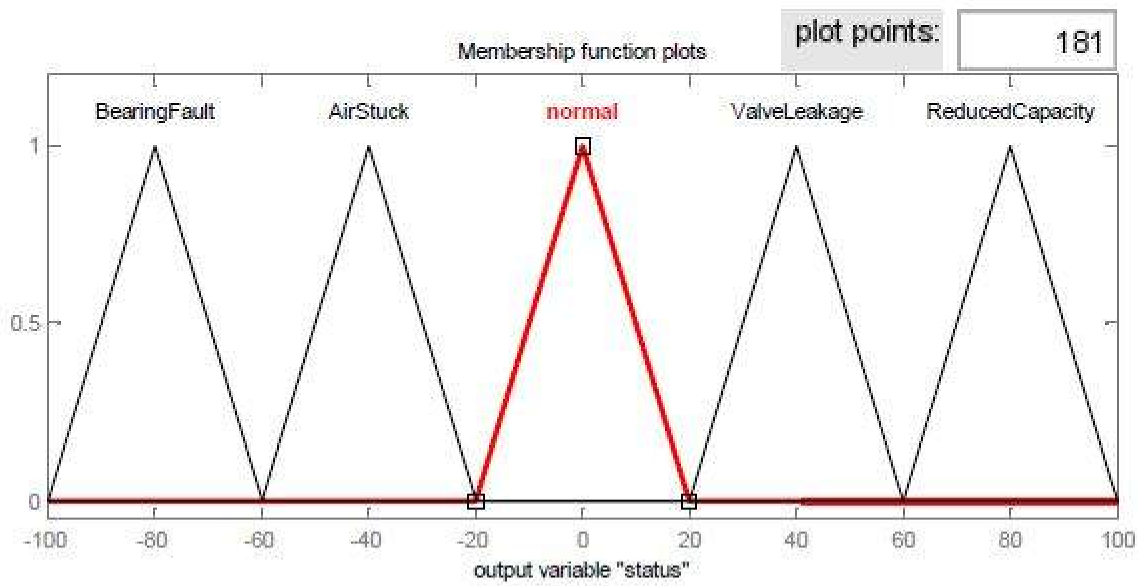


Fig 5.2.6 Membership function for output in fuzzy controller

6 RESULTS AND DISCUSSIONS

The system taken here for the analysis is HVAC (Heating, Ventilation and Air Conditioning). In present, no vibration data from the field plays a vital role for controlling the system. In traditional HVAC system, temperature, humidity, air flow rate, etc are taken for the design of the controller. Here, we are analyzing the vibration data and trying to put the results on optimizing the design of the controller.

The main problems that faced by HVAC system are given below. They are

1. Low heating/cooling capacity
2. Return air flow stuck
3. Valve leakage
4. Bearing fault of motor

By analyzing the vibration data from the field, It is possible to find the current status of the system. For this, only two vibrations are given to the fuzzy controller. One is from the shaft (shaft vibration) and second from duct(duct vibration).

Fig 6.1 Y2 series 3- phase induction motor

The motor used for the case study is a “Y2 series 3- phase induction motor” manufactured by Toptek private Ltd. And the vibration sensor used for the shaft vibration data is Model 622B01 - Platinum Precision Industrial ICP® Accelerometer manufactured by IMI sensors. For duct vibration data, ACC 320 general purpose accelerometer is used.

(a)

(b)

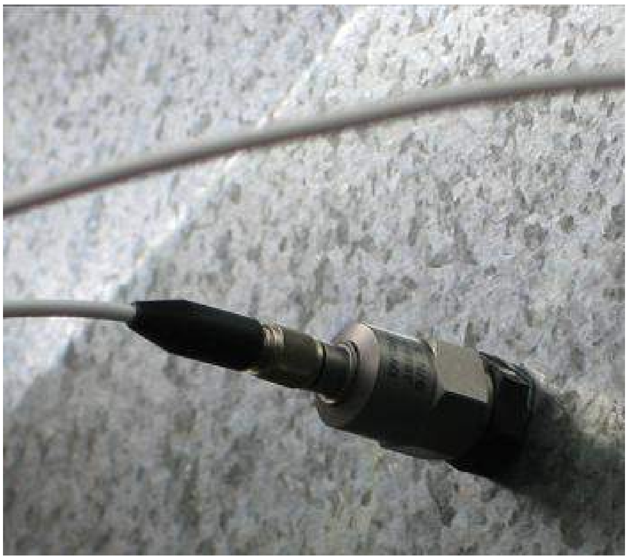
Fig. 6.2 (a) Accelerometer used for duct vibration data
(b) Accelerometer used for shaft vibration data

The model used for shaft vibration is of very high precision. The main features of this platinum precision industrial ICP are followed.

- Full frequency sweep calibration: 5% sensitivity deviation tolerance
- 15 kHz high frequency response
- Ideal for early detection of bearing fluting conditions
- Ideal for route-based data collection

The general purpose accelerometer is fixed at the duct. The location of the sensor is shown in figure 6.3(a) and (b). The picture was shot from the site. Where the sensor is installed by drilling the duct.

(a)



(b)

Fig. 6.3 (a) Location for the vibration sensor

(b) Installed sensor

Various data sets are collected for the normal and faulty conditions of the system. These data are then analyzed using MATLAB software. A sampling rate of 1000 was used for the data collection. The following are the data from the shaft of the motor.

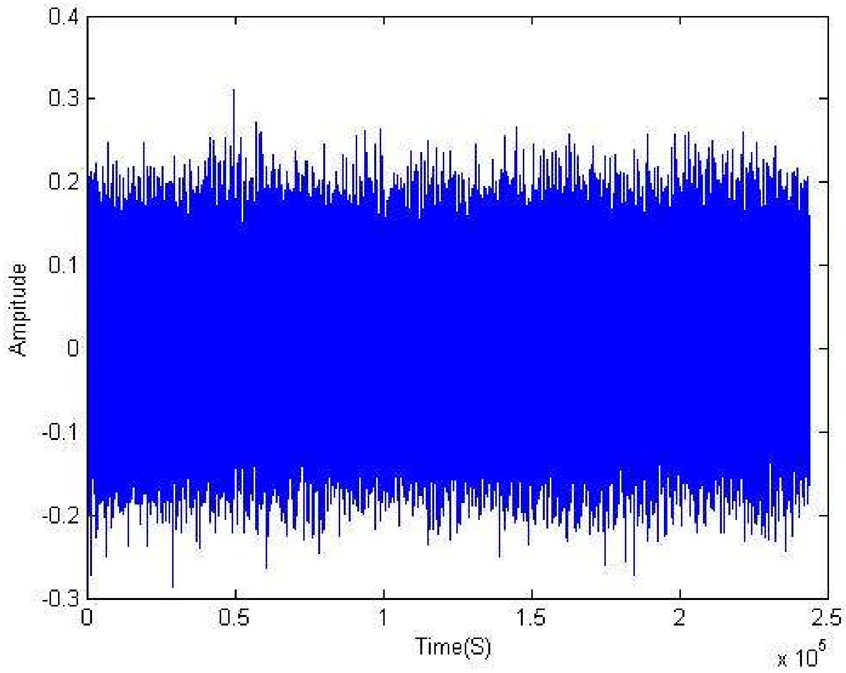


Fig. 6.4 Normal vibration data from shaft

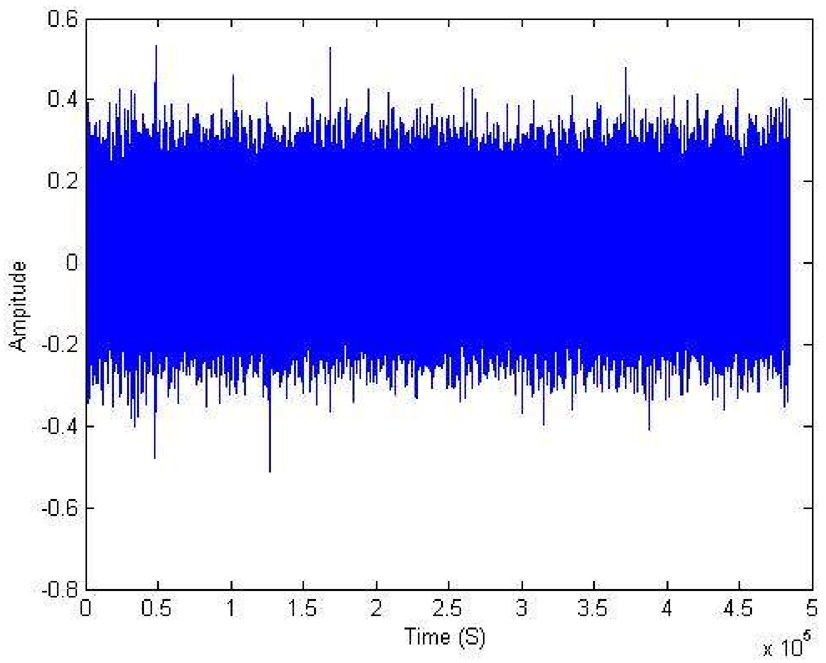


Fig. 6.5 Vibration data on bearing fault from shaft

The following figures shows the real time vibration data from the duct.

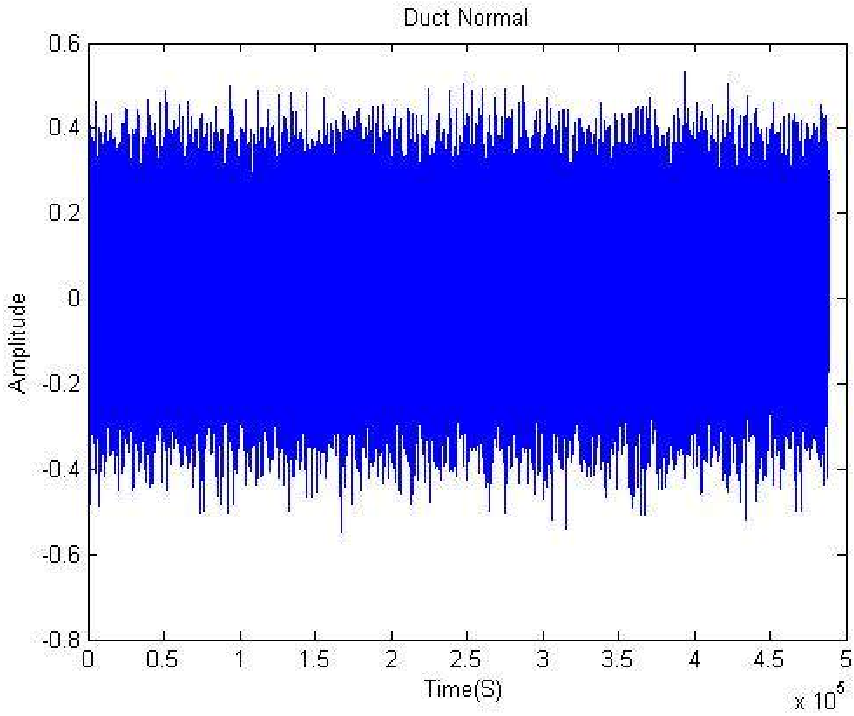


Fig. 6.6 Vibration data on normal condition from duct

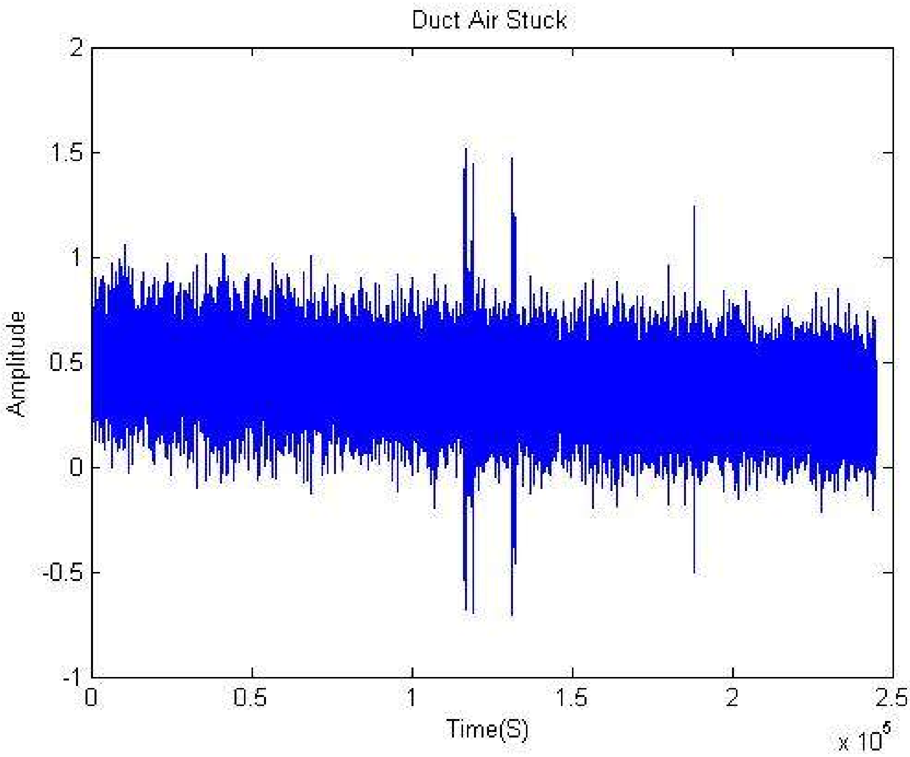


Fig. 6.7 Vibration data on return air stuck from duct

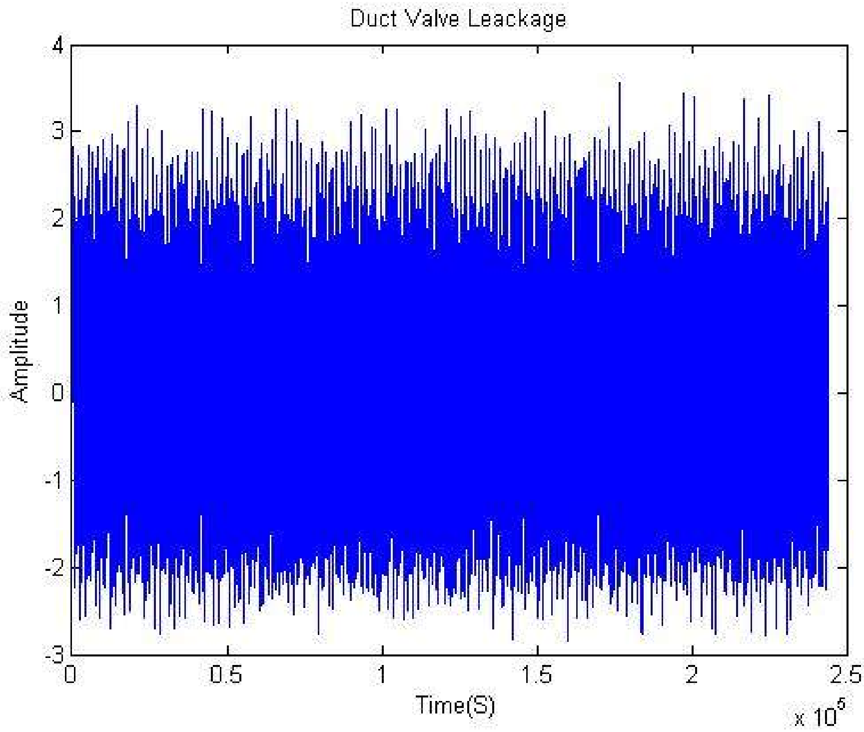


Fig 6.8 Vibration data on valve leakage from the duct

These are the real time vibration data from the site. Analysis was done on these time domain signals for the optimization of the system. The FFT of these signals are given as follows

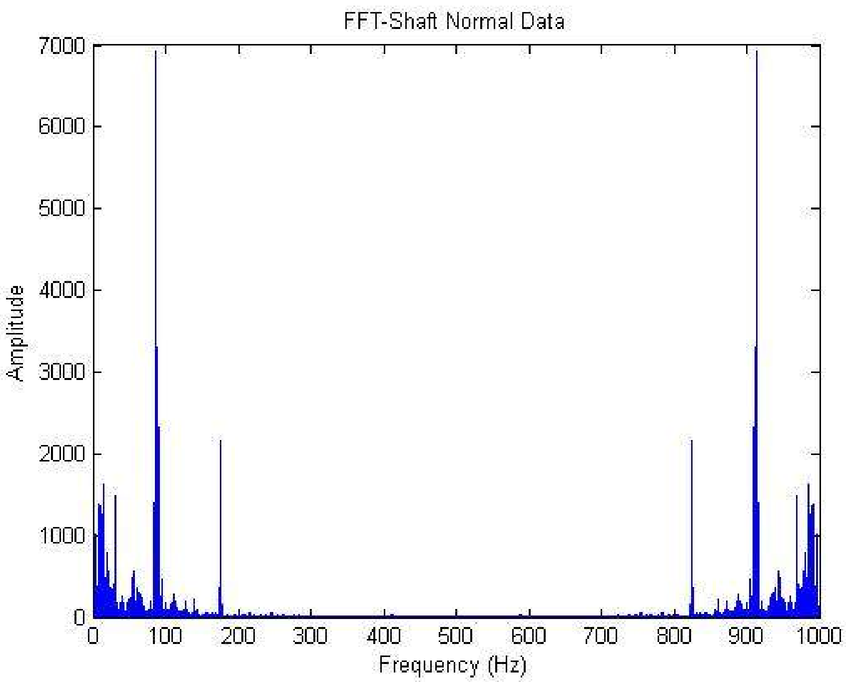


Fig 6.9 FFT of normal vibration data from shaft

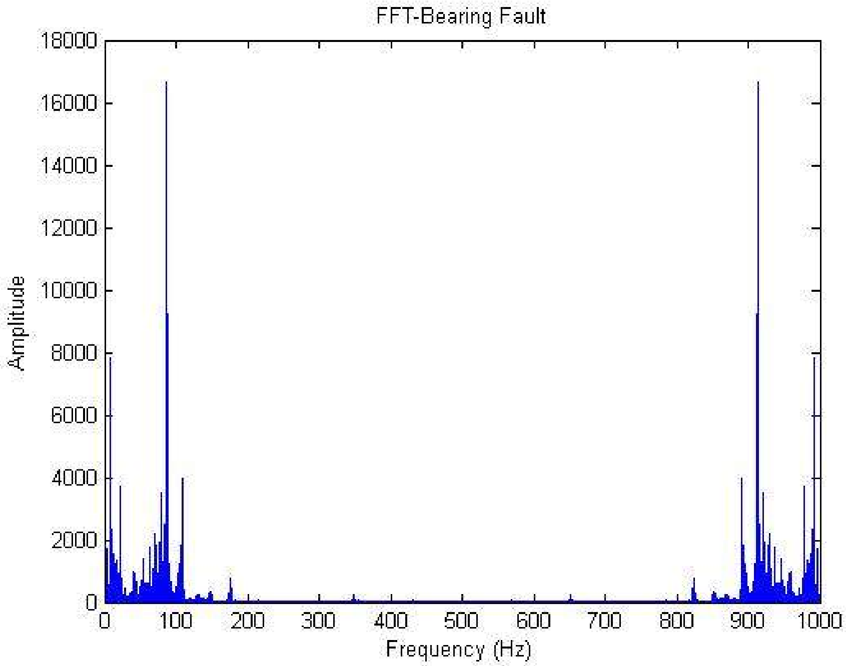


Fig 6.10 FFT of bearing fault data from shaft

By comparing the FFT of normal and bearing fault data, a clear difference in frequency range is detected. The initial frequencies shoots in the range of 7000 for normal condition while it shoots up to 18000 for the bearing fault condition. The same is repeated for the high frequency range also.

The vibration data from duct were also converted in to frequency mode. The below figure shows FFT of different conditions of the duct.

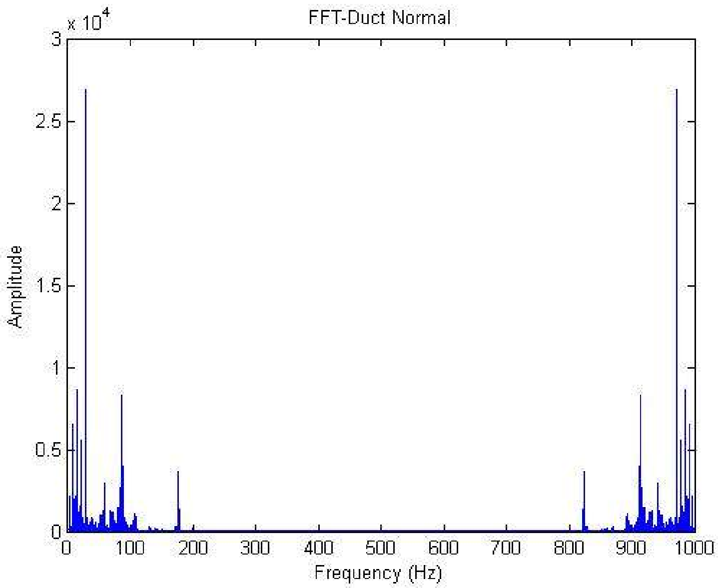


Fig 6.11 FFT of normal data from duct

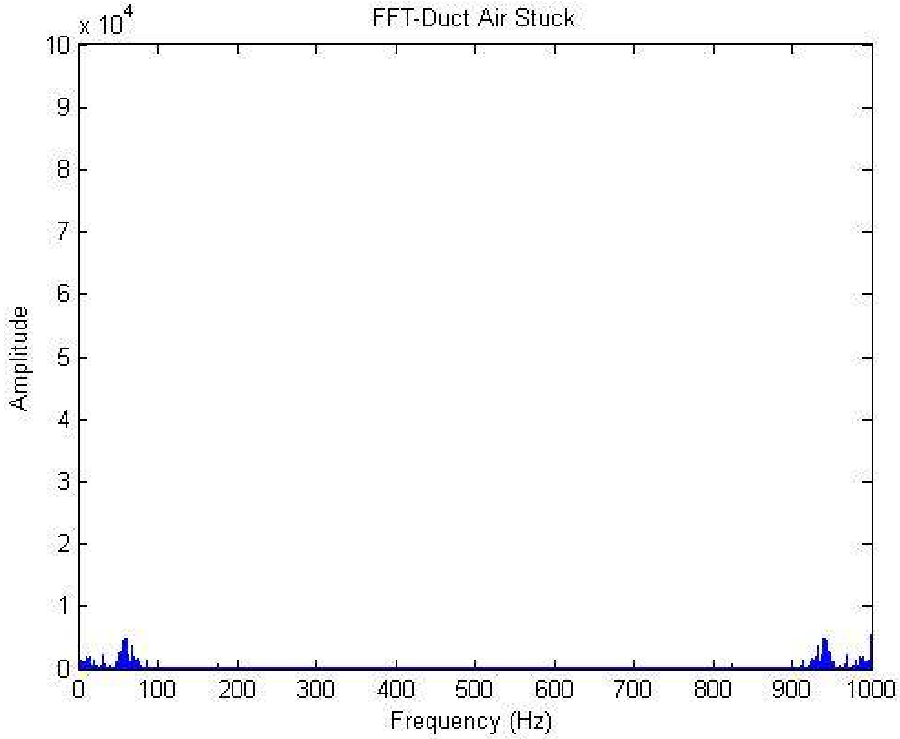


Fig 6.12 FFT of air stuck data from duct

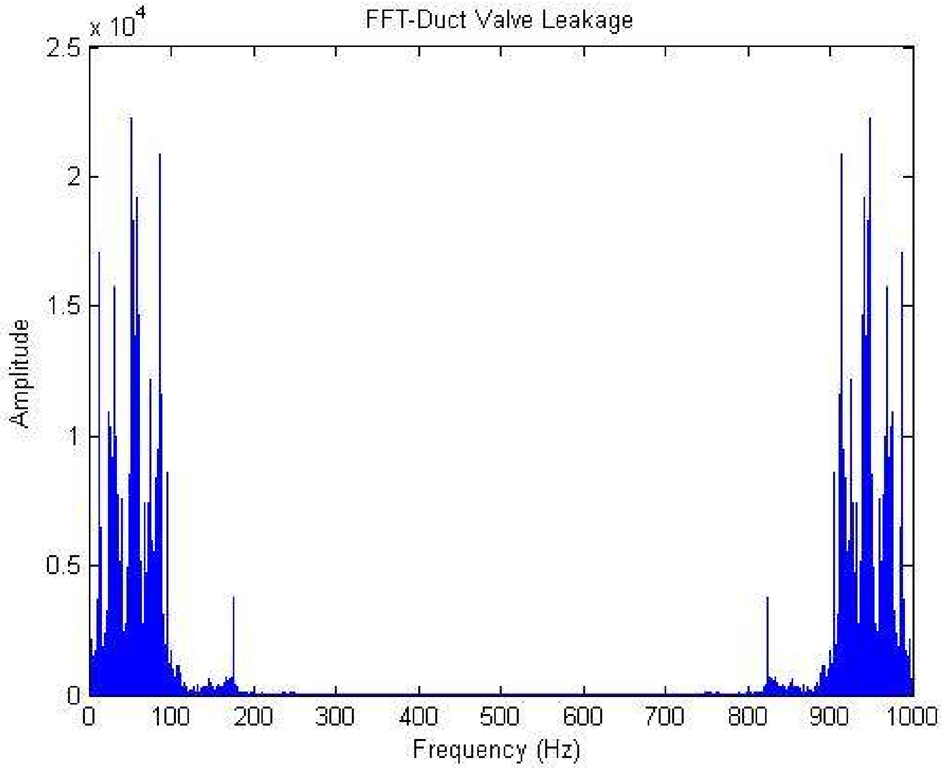


Fig 6.13 FFT of valve leakage data from duct

From frequency mode analysis of the duct vibrations, a classification for the two errors are possible. Analysing the frequency range and the rate of change of the frequency gives rise to easy way of calculating the error magnitude too.

Now consider some other time domain analysis for a better and fast controller. The data set is again divided in to small subsets of 1000 values each and then the analysis is done. The MATLAB program used for this also follows

```
Xm=[];Ym=[];
Xs=[];Ys=[];
Xk=[];Yk=[];
Xsk=[];Ysk=[];
Xmn=[];Ymn=[];
Xmx=[];Ymx=[];
Xv=[];Yv=[];
B=1000
for i=1:100
   x=normaldata1((i-1)*B+1:i*B);
   y=bearingfault1((i-1)*B+1:i*B);
   Xm= [Xm mean(x)]; Ym=[Ym mean(y)];
   Xs =[Xs std(x)]; Ys=[Ys std(y)];
   Xk =[Xk kurtosis(x)]; Yk=[Yk kurtosis(y)];
   Xsk =[Xsk skewness(x)]; Ysk=[Ysk skewness(y)];
   Xmn =[Xmn min(x)]; Ymn=[Ymn min(y)];
   Xmx =[Xmx max(x)]; Ymx=[Ymx max(y)];
   Xv =[Xv var(x)]; Yv =[Yv var(y)];
end
figure(1)
plot(Xm)
hold on
plot(Ym,'r')
hold off

figure(2)
```

```
plot(Xs)
hold on
plot(Ys, 'r')
hold off

figure(3)
plot(Xk)
hold on
plot(Yk,'r')
hold off

figure(4)
plot(Xsk)
hold on
plot(Ysk,'r')
hold off

figure(5)
plot(Xmn)
hold on
plot(Ymn,'r')
hold off

figure(6)
plot(Xmx)
hold on
plot(Ymx,'r')
hold off

figure(7)
plot(Xv)
hold on
plot(Yv,'r')
hold off
```

The following figure 6.14 shows the comparison of mean of the normal and bearing fault from the shaft signal.

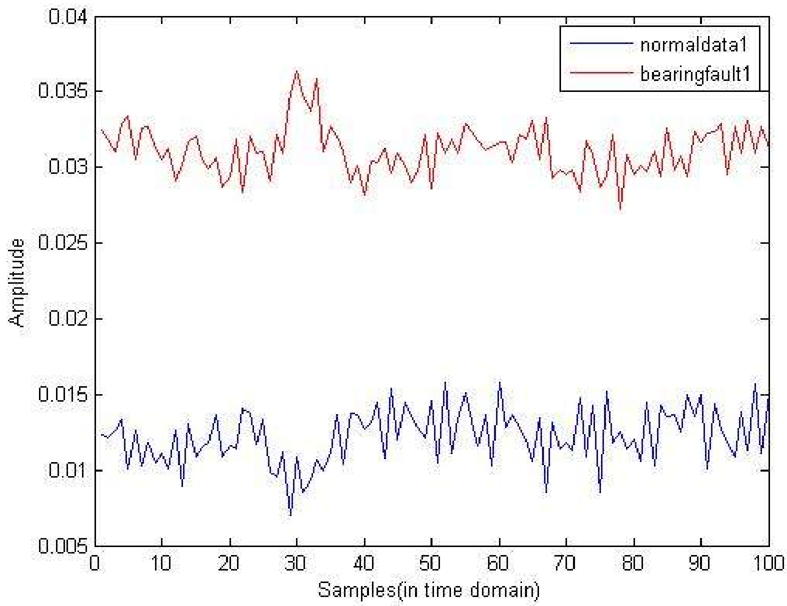


Fig 6.14 Mean of normal data and bearing fault data

The following figure 6.15 shows the comparison of standard deviation of a normal and bearing fault signal.

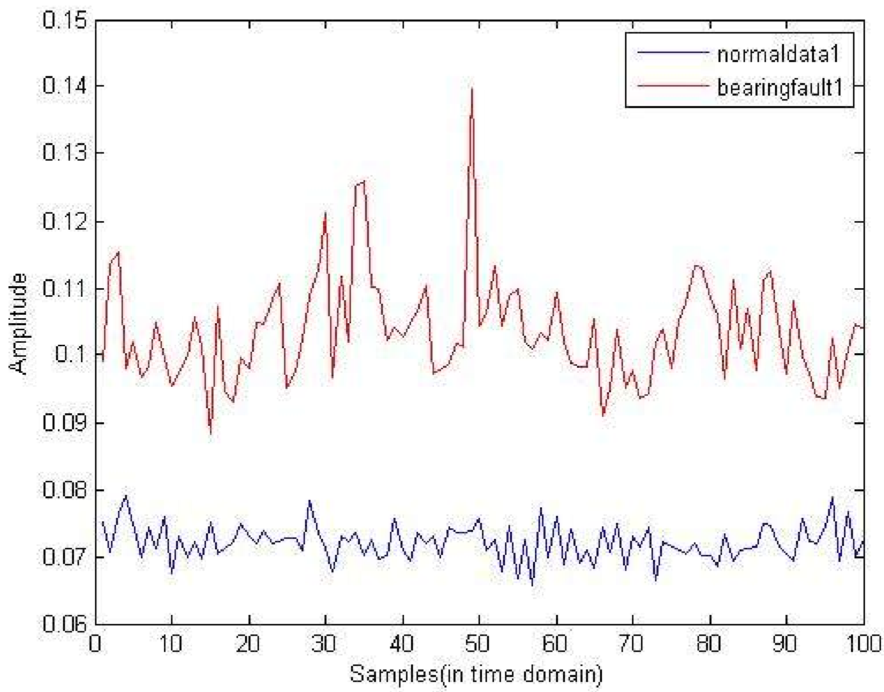


Fig 6.15 Standard deviation of normal data and bearing fault data

The following figure 6.16 shows the kurtosis analysis of the data for every 1000 set of vibration data

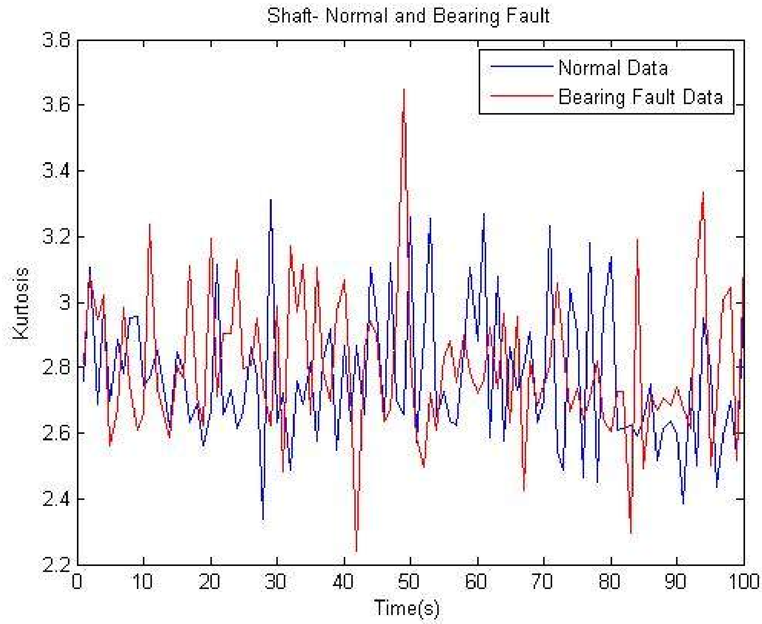


Fig 6.16   Kurtosis of Normal and Bearing Fault data from shaft

For the analysis for the skewness of the shaft vibration, the following comparison of graphs were analysed in figure 6.17

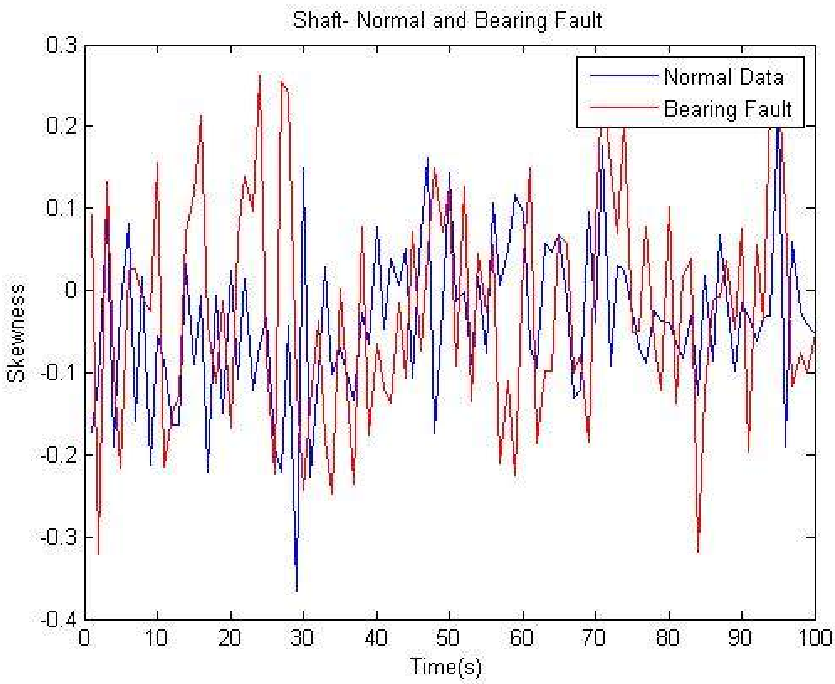


Fig 6.17   Skewness of normal data and bearing fault data from shaft

The following figure 6.18 shows the comparison of maximum peals of the vibration data for each 1000 samples.

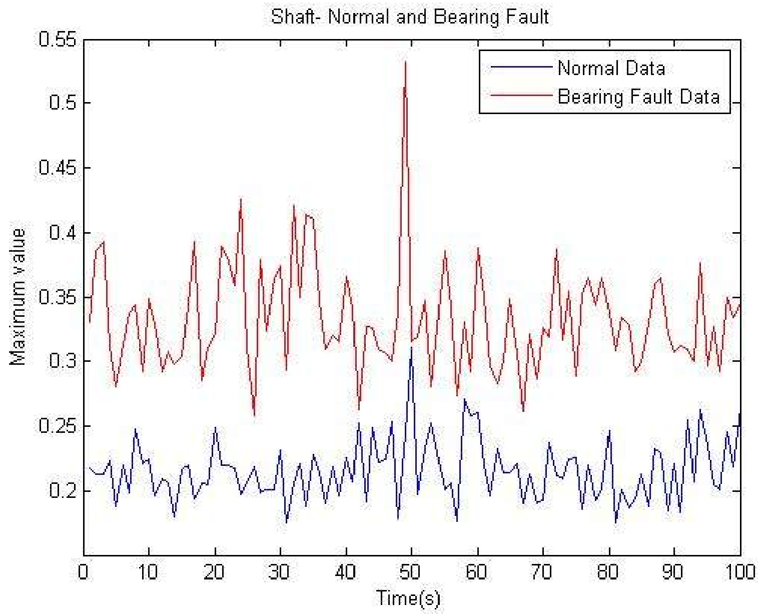


Fig 6.18 Maximum peaks value of normal data and bearing fault data from shaft

The following figure 6.19 shows the comparison between the minimum peaks of the normal and bearing fault data.

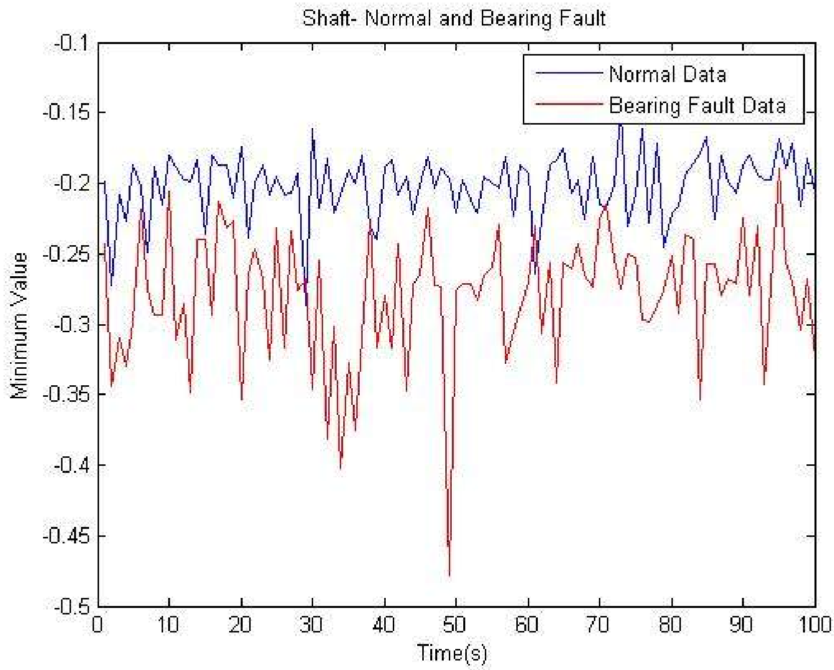


Fig 6.19 Minimum peaks of normal data and bearing fault data

The comparison of the variance of normal and error mode vibration data is showed in figure 6.20

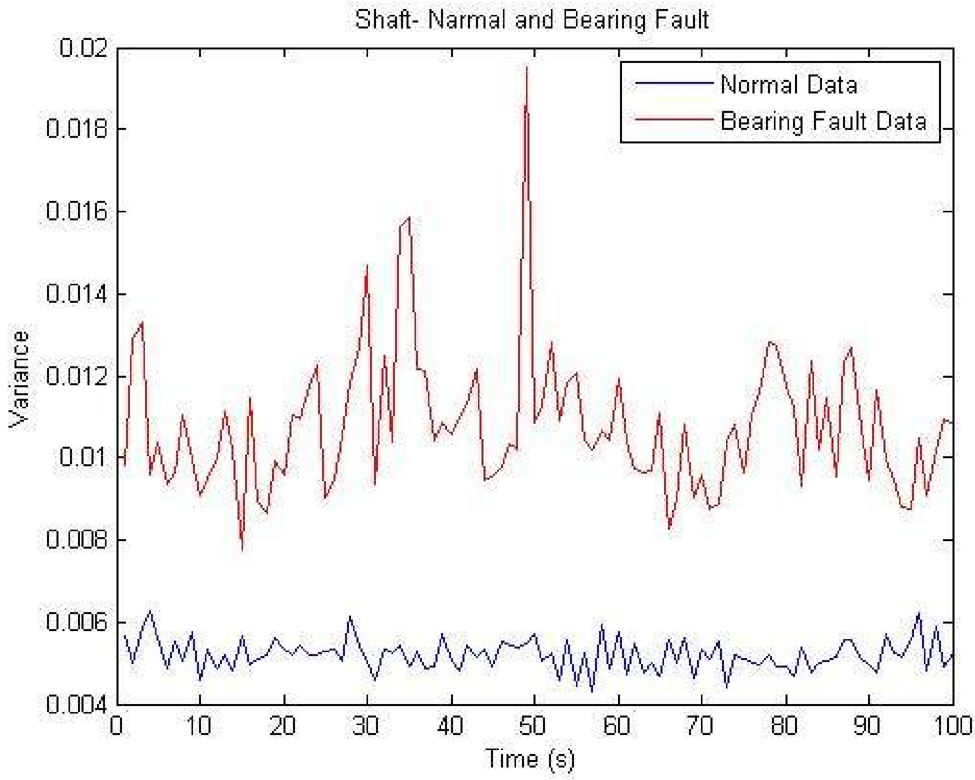


Fig 6.20 Variance of normal and bearing fault data from shaft

From the analysis, we will be able to find the difference between the two conditions of the motor. From all these data analysis, a rule set is made for the fuzzy controller for an optimized system. The fuzzy rules are made from the time and frequency mode analysis of the data from the shaft and the duct.

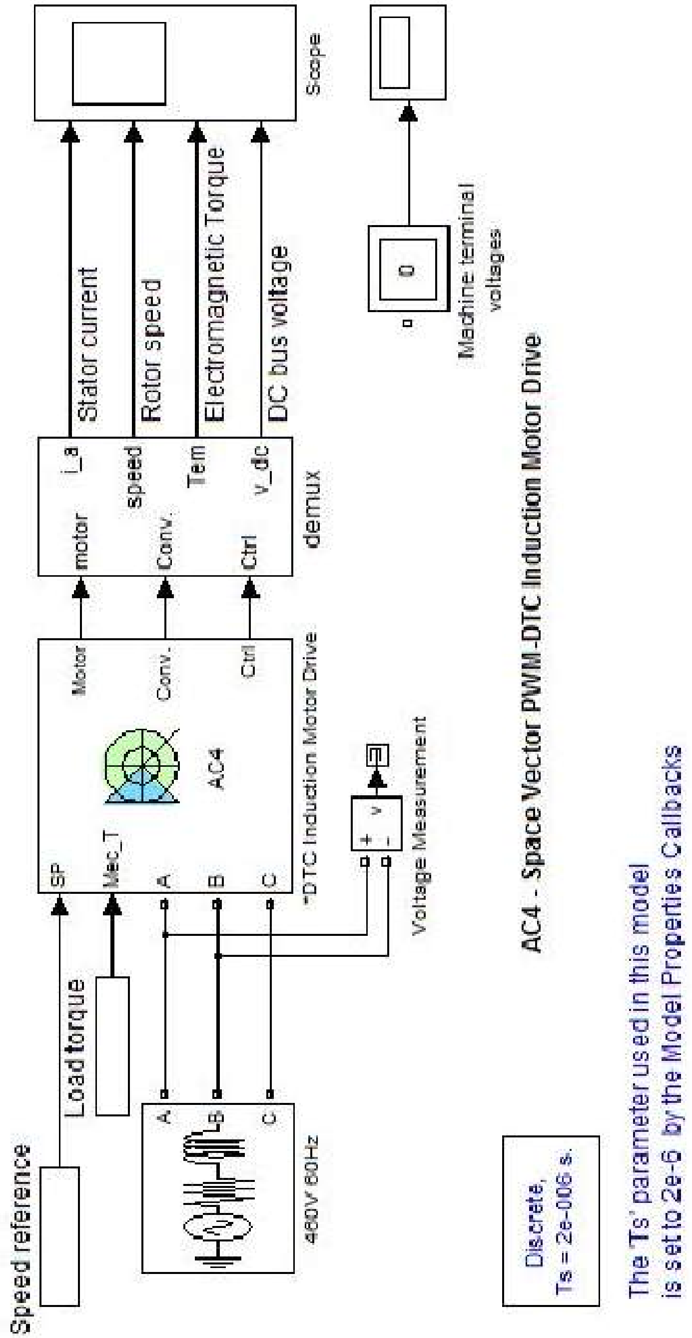


Fig. 6.21 Speed controller simulation of induction motor

The figure 6.21 shows the SIMULINK circuit for the speed control of induction motor. The induction motor used in the HVAC system is modelled here. A fuzzy controller is designed using the above mentioned analysis and this controller is employed in the motor drive. The input and output of the fuzzy controller is given below.

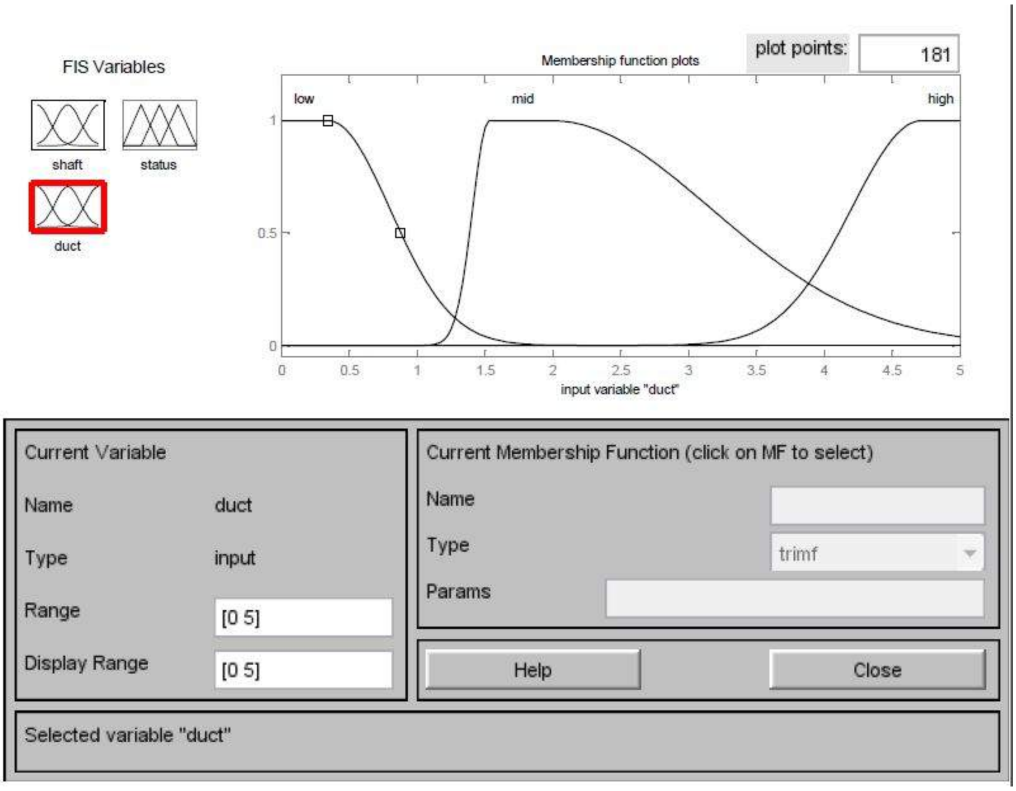


Fig 6.22 Fuzzy input for duct vibration

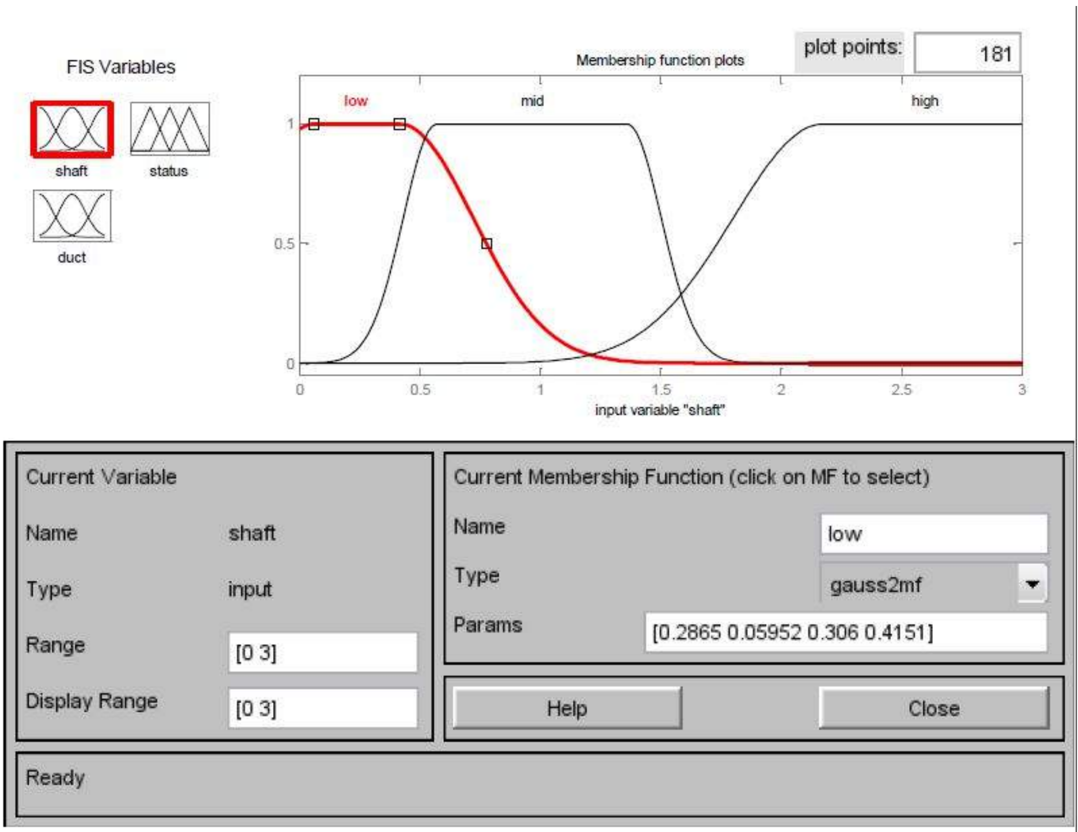


Fig 6.23 Fuzzy input for shaft

Fig 6.24 Fuzzy output diagram

The following figure 6.25 shows the fuzzy surface of the system. The rules are made from the analysis done on the vibration signal.

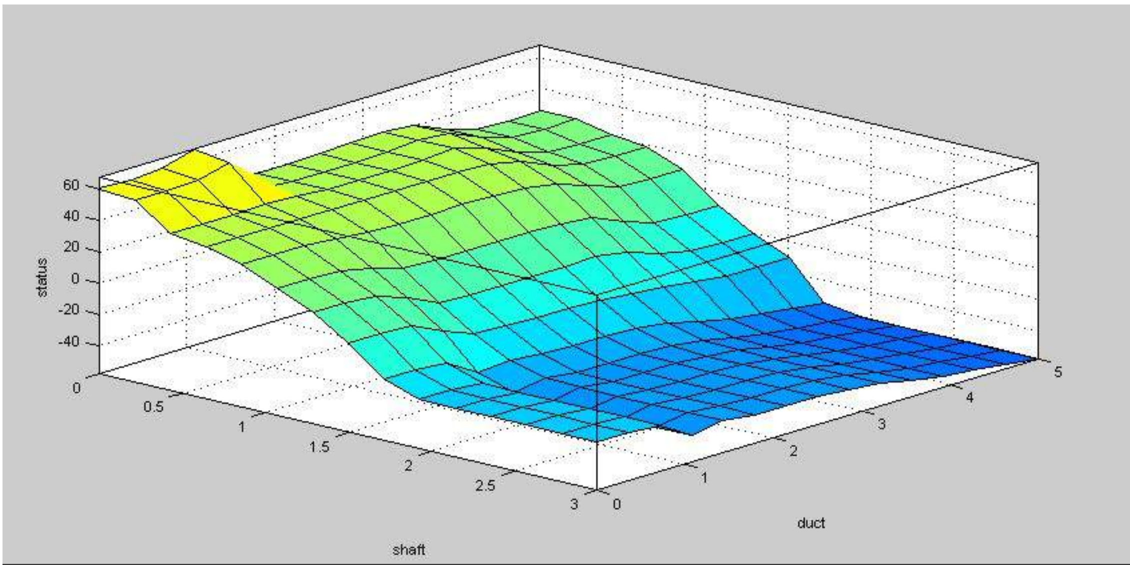


Fig 6.25 Fuzzy surface

The rules for the fuzzy controller in frequency mode is given below

1. If (shaft is mid) and (duct is low) then (status is ValveLeakage) (1)
2. If (shaft is mid) and (duct is mid) then (status is normal) (1)
3. If (shaft is mid) and (duct is high) then (status is AirStuck) (1)
4. If (shaft is low) and (duct is mid) then (status is ReducedCapacity) (1)
5. If (shaft is high) and (duct is mid) then (status is BearingFault) (1)
6. If (shaft is low) and (duct is low) then (status is ValveLeakage) (1)
7. If (shaft is low) and (duct is high) then (status is ValveLeakage) (1)
8. If (shaft is high) and (duct is low) then (status is AirStuck) (1)
9. If (shaft is high) and (duct is high) then (status is AirStuck) (1)
10. If (duct is low) then (status is ValveLeakage) (1)
11. If (duct is mid) then (status is normal) (1)
12. If (duct is high) then (status is AirStuck) (1)
13. If (shaft is low) then (status is ReducedCapacity) (1)
14. If (shaft is mid) then (status is normal) (1)
15. If (shaft is high) then (status is BearingFault) (1)

Here the FFT of the vibration signal is analysed and decisions are made as per the rules. The bearing fault results in a value between -100 to -80 at the output of the fuzzy controller. this means it reduces the rotation of the motor to save the motor from unwanted condition due to bearing fault. Th other values returned by controller for each faults are given below.

Bearing fault	:	-250 to -150
Air stuck	:	-150 to -50
Normal	:	-50 to 50
Valve leakage	:	50 to 150
Reduced capacity	:	150 to 250

Another controller is also designed as per the time domain analysis. The following figure 6.26 shows the input and output modules of the controller. The mean, standard deviation, variance, minimum and maximum values are given as the input to the system

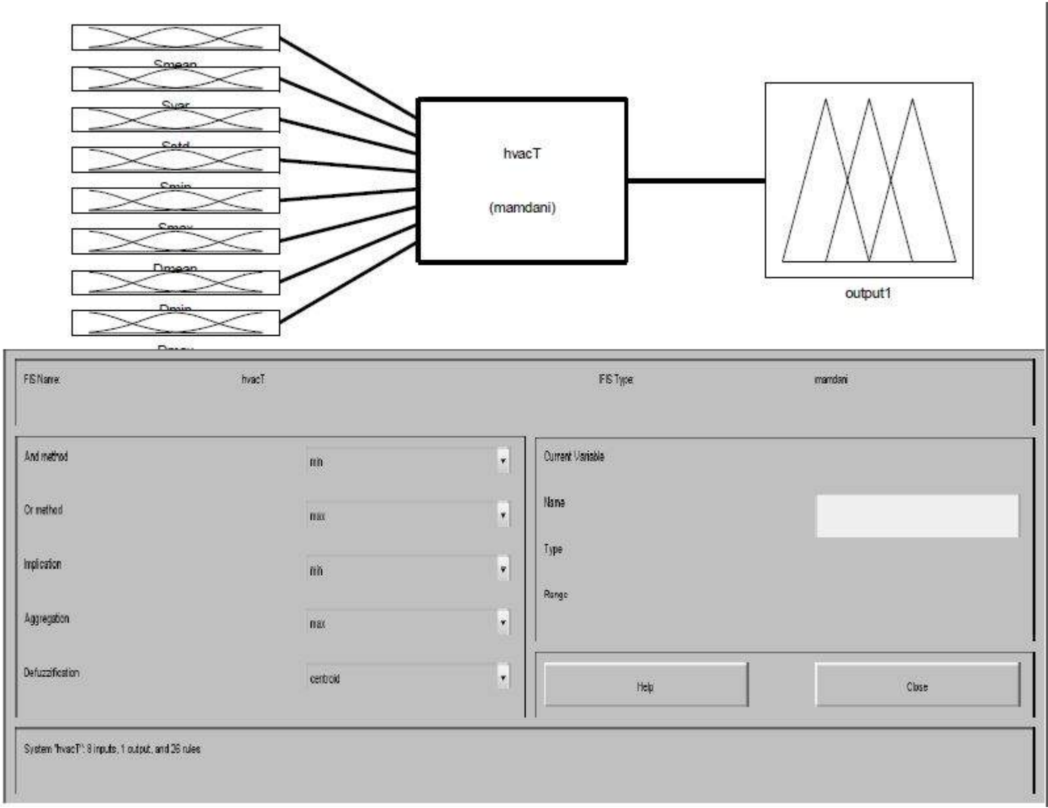


Fig 6.26 Fuzzy controller for time domain signal control

The rule set are given below for that controller.

1. If (Smean is normal) and (Svar is normal) and (Sstd is normal) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is normal) (1)
2. If (Smean is fault) and (Svar is normal) and (Sstd is normal) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
3. If (Smean is fault) and (Svar is fault) and (Sstd is normal) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
4. If (Smean is fault) and (Svar is fault) and (Sstd is fault) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
5. If (Smean is fault) and (Svar is fault) and (Sstd is fault) and (Smin is fault) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)

6. If (Smean is fault) and (Svar is fault) and (Sstd is fault) and (Smin is fault) and (Smax is fault) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
7. If (Smean is fault) and (Svar is fault) and (Sstd is fault) and (Smin is normal) and (Smax is fault) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
8. If (Smean is fault) and (Svar is fault) and (Sstd is normal) and (Smin is normal) and (Smax is fault) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
9. If (Smean is fault) and (Svar is normal) and (Sstd is normal) and (Smin is normal) and (Smax is fault) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
10. If (Smean is normal) and (Svar is normal) and (Sstd is normal) and (Smin is normal) and (Smax is fault) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
11. If (Smean is normal) and (Svar is normal) and (Sstd is normal) and (Smin is fault) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
12. If (Smean is normal) and (Svar is normal) and (Sstd is fault) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
13. If (Smean is normal) and (Svar is fault) and (Sstd is normal) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
14. If (Smean is normal) and (Svar is fault) and (Sstd is fault) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
15. If (Smean is normal) and (Svar is fault) and (Sstd is fault) and (Smin is fault) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
16. If (Smean is normal) and (Svar is fault) and (Sstd is fault) and (Smin is fault) and (Smax is fault) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)

17. If (Smean is normal) and (Svar is normal) and (Sstd is fault) and (Smin is fault) and (Smax is fault) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
18. If (Smean is normal) and (Svar is normal) and (Sstd is normal) and (Smin is fault) and (Smax is fault) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
19. If (Smean is normal) and (Svar is normal) and (Sstd is normal) and (Smin is normal) and (Smax is fault) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
20. If (Smean is normal) and (Svar is normal) and (Sstd is fault) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_low) (1)
21. If (Smean is normal) and (Svar is normal) and (Sstd is normal) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is fault) and (Dmax is normal) then (output1 is speed_high) (1)
22. If (Smean is normal) and (Svar is normal) and (Sstd is normal) and (Smin is normal) and (Smax is normal) and (Dmean is normal) and (Dmin is normal) and (Dmax is fault) then (output1 is speed_high) (1)
23. If (Dmean is normal) and (Dmin is normal) and (Dmax is normal) then (output1 is normal) (1)
24. If (Dmean is fault) and (Dmin is normal) and (Dmax is normal) then (output1 is speed_high) (1)
25. If (Dmean is normal) and (Dmin is fault) and (Dmax is normal) then (output1 is speed_high) (1)
26. If (Dmean is normal) and (Dmin is normal) and (Dmax is fault) then (output1 is speed_low) (1)
27. If (Dmean is normal) and (Dmin is normal) and (Dmax is fault) then (output1 is speed_high) (1)

The simulink diagram for the fuzzy controller is given below in figure 6.27.

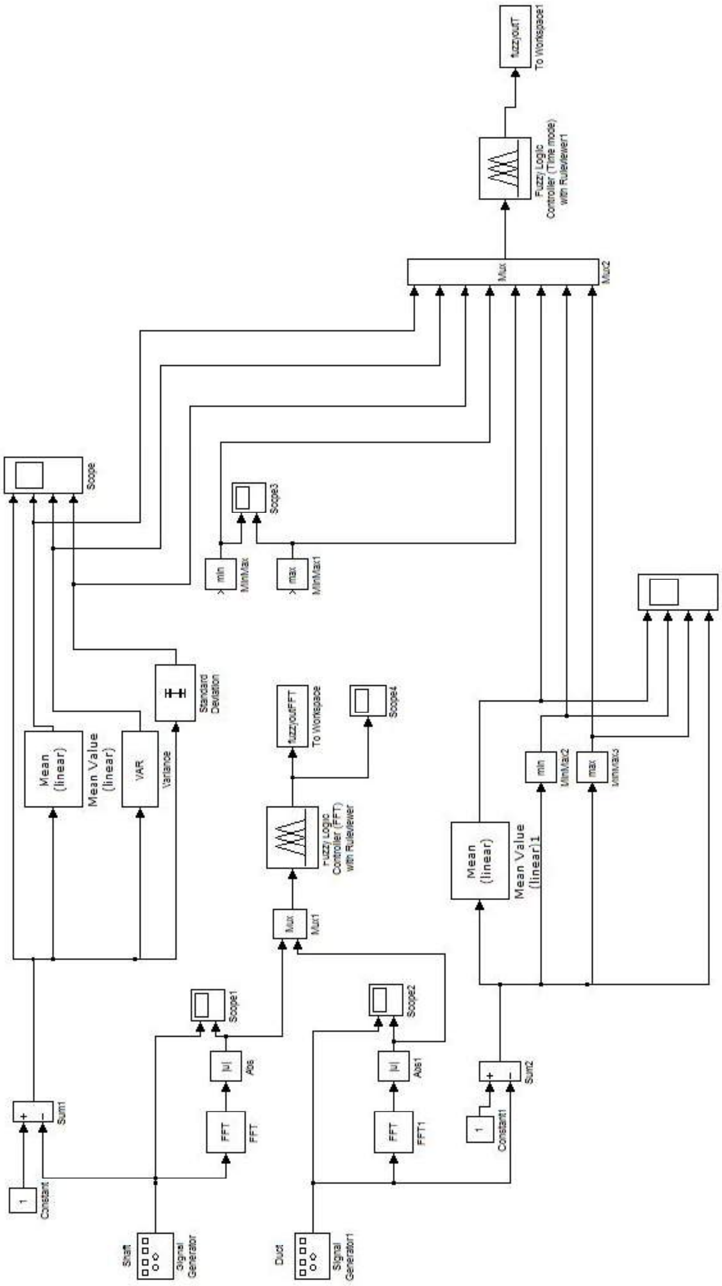


Fig 6.27 SIMULINK diagram for fuzzy controller

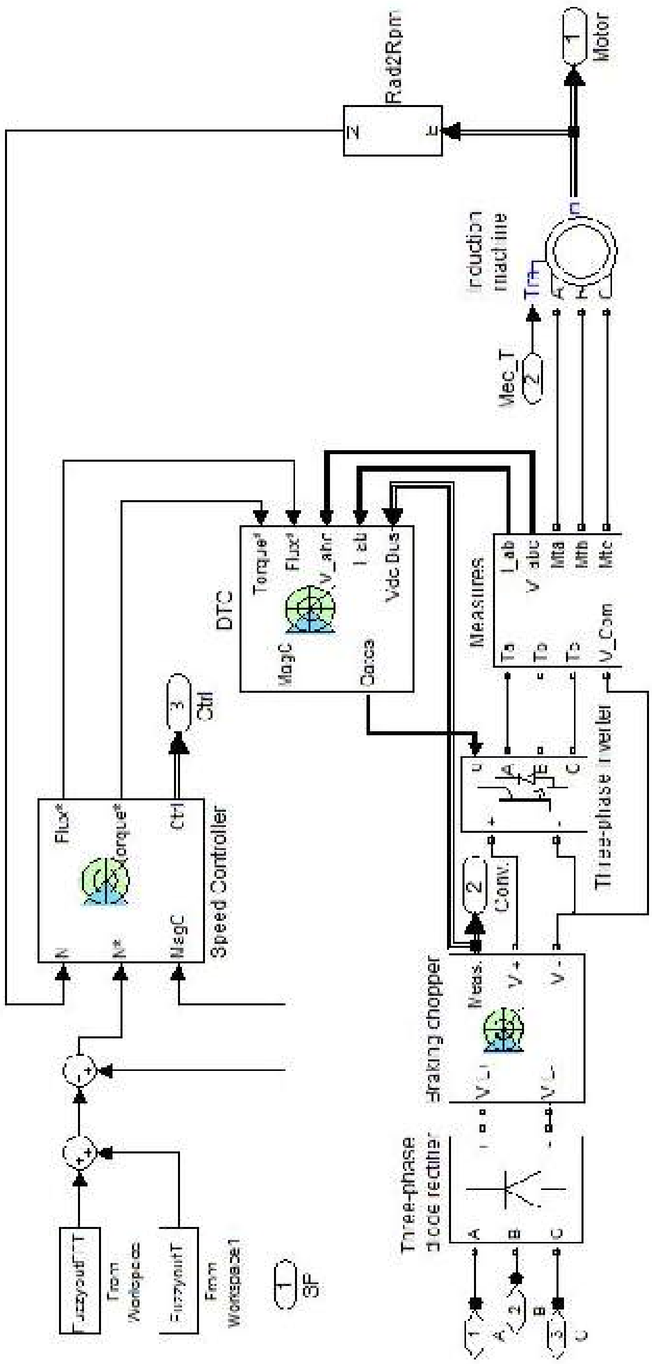


Fig 6.28 Induction motor drive using Fuzzy controller

The following output was got from the system. The RPM of rotor, stator current, electromagnetic torque and DC bus voltage are plotted in the graph.

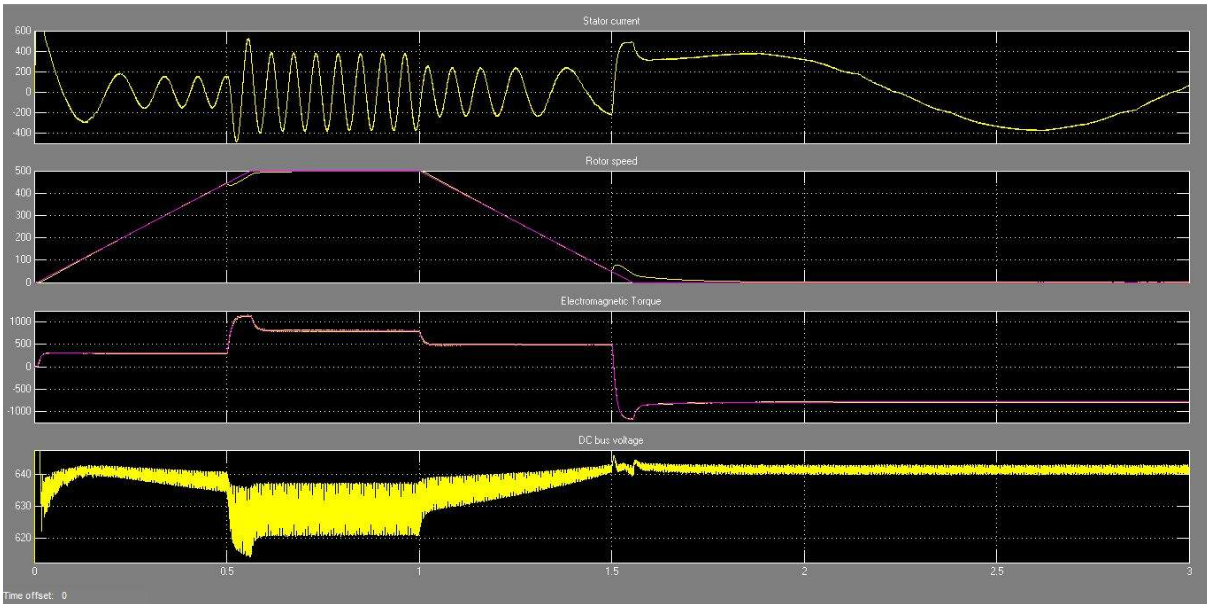


Fig 6.29 Result of MATLAB/SIMUINK simulation

7 CONCLUSIONS

Thus the vibration signals from the HVAC system are measured, analyzed and a fuzzy controller is designed using the analytical data. The mathematical parameters of the vibration data were analysed and classified the errors of the devices. A controller is designed as per the analysis made on the vibration data collected from the field. A beginning has been made to provide an integrated environment for analyzing vibration signals of various frequency bands. The following conclusions were made from the experience.

- Spectral ordinate method of distinguishing signal from noise
- Prediction error method of distinguishing signal from noise. This will lead to detection of fault on an earlier state and further improved performance.
- Estimation of magnitude of the vibrating signal.
- Distinction between different kind of vibrations.
- Online detection and estimation of the magnitude of vibrations.
- The characteristics of the electrical machines can be improved further more if a more accurate vibration analyzing methodology is employed.
- The vibration monitoring can be interfaced with SCADA or any other monitoring system and that can help for further improvement of the system.

8 REFERENCE

[1] D.-H. Lee J.H. Lee J.-W. Ahn, " Mechanical vibration reduction control of two-mass permanent magnet synchronous motor using adaptive notch filter with fast Fourier transform analysis" Published in IET Electric Power Applications,Received on 20th October 2011,Revised on 9th January 2012,doi: 10.1049/iet-epa.2011.0322

[2] Choi, H.H., Vu, N.T.T., Jung, J.W.: 'Digital implementation of an adaptive speed regulator for a PMSM', IEEE Trans. Power Electron., 2011, 26, (1),

[3] Orlowska-Kowalska, T., Dybkowski, M., Szabat, K.: 'Adaptive slidingmode neuro-fuzzy control for the two-mass induction motor drive without mechanical sensors', IEEE Trans. Ind. Electron., 2010.

[4] Dr Michael Sek, "Frequency Analysis – Fast Fourier Transform (FFT)", , IEEE Trans. Ind. Electron., 2009.

[5] B. P. Dubey, S.D. Dhodapkar and R.K. Patil,"The vibration signal analyser using fourier transformation and ANN(ViSFoTA) package",2008.

[6] M P Norton and D G Karczub , "Fundamentals of Noise and Vibration Analysis for Engineers," (CUP, 2003)(ISBN 9780521495615)(O)(651s)

[7] Satomi Hattori, Muneaki Ishida and Takamasa Hori ," Suppression Control Method of Torque Vibration for Brushless DC Motor Utilizing Repetitive Control with Fourier Transform"- Trans. of the Society of Instrument and Control Engineers Vol.E-2, No.1, 42/53 (2002)

[8] T. Kosaka, N. Matsui, Y. Taniguchi and H. Do-meki, "Some Considerations on Torque Ripple Suppression of Reluctance Motors", T. IEE Japan, Vol.118-D, No.2, 1998.

[9] T. Hanamoto, H. Ikeda, Y. Tanaka and T Mochizuki, "Small Vibration Suppression Control of Brushless DC Motors with Periodical Disturbance," T. IEE Japan, Vol.117-D, No.3, 1997.

[10] M. Caudill and C. Butler, "Understanding Neural Networks - Computer explorations", Volume 1 & 2, MIT Press, 1992.

[11] K. Kamiya, M. Shigyo, T. Makino and N. Matsui, "DSPBased High Precision Torque Control of Permanent Magnet DD Motor," T. IEE Japan, Vol.110-D, No.2, 1990.

[12] V. Muralidharan, V. Sugumaran, A comparative study of Naïve Bayes classifier and Bayes net classifier for fault diagnosis of monoblock centrifugal pump using wavelet analysis, Applied Soft Computing 12 (8) (2012) 2023–2029.

[13] Jiangping Wang, Hongtao Hu, Vibration-based fault diagnosis of pump using fuzzy technique, Measurement 39 (2006) 176–185.

[14] B. Samanta, K.R. Al-Baulshi, Artificial neural network based fault diagnostics of rolling element bearings using time domain features, Mechanical Systems and Signal Processing 17 (2003) 317–328.

[15] V. Muralidharan, V. Sugumaran, Feature extraction using wavelets and classification through decision tree algorithm for fault diagnosis of mono-block centrifugal pump, Measurement 46 (2013) 353–359.

[16] Fansen Konga, Ruheng Chen, A combined method for triplex pump fault diagnosis based on wavelet transform, fuzzy logic and neuralnetworks, Mechanical Systems and Signal Processing 18 (2004) 161– 168.

[17] L.B. Jack, A.K. Nandi, Comparison of neural networks and support vector machines in condition monitoring application, in: Proceedings of COMADEM 2000, Houston, TX, USA, 2000, pp. 721– 730.

[18] M. Ning , M. Zaheeruddin , Z. Chen ”Fuzzy-Set Based HVAC System Uncertainty Analysis” Published by IEEE, 2006.

[19] T. I. Salsbury, R. C. Diamond “Fault Detection In Hvac Systems Using Model based Feedforward Control” , published by IEEE, 2004.

[20] Vijay Prakash Pandey and Prashant Kumar Choudhary “Induction Motor Condition Monitoring Using Fuzzy Logic” , ISSN 2231-1297, Volume 3, Number 6 (2013), © Research India Publications.