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Electrical Fault Detection in Three Phase Squirrel Cage Induction Motor by Vibration Analysis using MEMS Accelerometer.

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Abstract - **The ever increasing applications of 3phase Induction motor have resulted in a growing awareness on addressing various performance demands. The condition monitoring of these electrical machines has received considerable attention in recent years. The diagnostics based on vibrations produced by these motors can form valuable data for preventive maintenance of these machines. The vibration analysis demands appropriate vibration transducer. With the advent of MEMS [Micro Electro Mechanical Systems], Technology I.C. chip mounted accelerometers are available. These accelerometers are having merits of low cost, high reliability, and low power consumption when compared to piezoelectric types which are conventionally used earlier. These accelerometers are gaining wide acceptance in condition monitoring of electrical machines. This paper presents the instrumentation developed around MEMS accelerometer and also proposes a technique of detecting abnormal electrical operating conditions in 3phase Induction motor such as single phasing, voltage unbalance by employing spectrum analysis of vibrations measured through MEMS accelerometer.**

Key words - MEMS accelerometer, single phasing, Motor current signature analysis, condition monitoring

I. INTRODUCTION

The 3 phase squirrel cage Induction motors are widely used in industry due to their reliability, low cost and robustness and hence treated as 'work horses' of industry [1, 4, 7]. But the possibility of faults is unavoidable. However, diagnosis and isolation of both electrical and mechanical faults of an induction motor is a challenging problem. Early fault detection allows preventive maintenance to be scheduled for motors which are not ordinarily due for service. It may also prevent extended periods of downtime caused by extensive motor failure or even catastrophic consequences caused by the failure of a motor. In order to detect the abnormality in induction motors several approaches are followed in practice.

Conventional methods are basically categorized as invasive and non-invasive techniques. Traditionally, the Motor Current Signature Analysis [MCSA] has been used for non-invasive detection of electrical and mechanical faults of induction motor. Other conventional methods include vibration analysis, and axial flux monitoring. The vibration analysis is still considered to be valuable in practice. Several works reported by researchers emphasize this fact. B.Liang et.al. [1] Carried out the vibration analysis using piezoelectric sensors to detect the induction motor asymmetrical faults such as rotor bar damage & asymmetrical supply voltage. They have made the comparison of this result with Phase current analysis and transient rotor speed analysis. C.Wang et.al. [2] have investigated the vibro-acoustic behavior of inverter driven induction motor. Authors have shown that these studies can be done by using structural analysis of induction motor using FEM technique and experimental model testing. Hasan, Oak et.al. [4] Used vibration analysis using accelerometer for the bearing faults in induction motor and studied the bad effects of bearing failures in induction motor. The published literature show that past investigators have proposed methods for detection of the asymmetrical rotor faults in induction motor using vibration analysis and as such no electrical asymmetrical faults are detected using vibration analysis. This paper proposes extension of vibrations analysis to detect single phasing and supply unbalance conditions. Further, the application of MEMS accelerometer [9] in vibration analysis of induction motor has not been reported.

Owing to the increase in economic pressure and frustrating vibration problems in Induction motor [5], a low cost and more reliable method is desirable for diagnostic studies. This demands a good accelerometer for vibration measurement. The accelerometer based on MEMS technology is gaining popularity due to low cost, high reliability, and low power consumption [9]. Recent developments in MEMS technology shows increasing trend in integration of miniature transducers along with signal conditioners in a single chip. This paper explores use of MEMS accelerometer and presents the experimental results of detecting single phasing and unbalanced supply voltage conditions of operation of induction motor.

II. EFFECTS OF SINGLE PHASING & VOLTAGE UNBALANCE [8]

The unbalance voltage and phase failure are similar phenomena, differing only in degree of unbalance. The unbalanced phase voltages or currents are readily identified, by the presence of negative phase sequence component. When the voltages supplied to an operating motor become unbalanced, the positive sequence currents remains substantially unchanged and negative sequence current flows due to the unbalance. If nature of the unbalance is open circuit in any phase, a negative sequence current flows that is equal and opposite to the previous load current in that phase. The combination of positive and negative sequence currents produces theoretical phase currents of approximately 1.7 times previous load in each sound phase and zero current in open phase. This is illustrated in fig.1, 2 & 3. Due to additional motor losses, the actual value of the motor phase

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current in each sound phase is closer to twice the previous load current. When an Induction motor loses one phase its slip increases but it is usually doesn't stall unless the resulting single phase supply voltage is below normal or the shaft load is more than 80% of full load. The losses increase significantly when loaded near or above its rating. Single phasing is a hazardous condition and steps should be taken to de energize the motor.

A small voltage unbalance produces a large negative sequence current flow in induction motor that will produce excess heating in the stator winding and rotor bars, but will not produce useful power output. De-rating of the motor is necessary when unbalanced voltages exceed 1% as defined by fig. 4. The per unit negative sequence impedance is approximately equal to the reciprocal of the rated voltage. The 5% voltage unbalance produces a stator negative sequence currents of 30% of full load current. The severity of this condition is indicated by the fact that with this extra current, the motor experiences a 40% to 50% increase in temperature rise. The increase in loss is largely in the rotor. Negative sequence phase currents produce a flux that rotates in a direction opposite to the rotor rotation. This flux cuts the rotor bars at a very high speed and generates a pronounced voltage resulting in a large rotor current. addition, 100Hz (50Hz fundamental) nature of the induced currents produces a marked skin effect in the rotor bars, greatly increasing rotor resistance. The rotor heating is substantial for minor voltage unbalance. Excessive heating may occur with phase current less than the rated current of the motor.

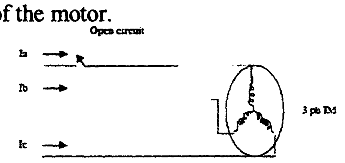

Fig.1: Current in motor windings with one phase open circuited; Wye connected motor.

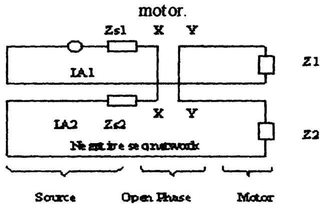

Fig.2. Connection of sequence networks for open phase condition.

This condition produces increased heating, increased energy consumption and lower efficiency. It is important to note that, a 2% voltage unbalance can produce as much as 10% increased losses in the machine. The net torque developed at any slip is given by

$$T \alpha [|I_F|^2 Z_f - |I_B|^2 Z_b] \qquad (1)$$

At starting for s = 1, R_f and R_b are equal. The V_F and V_B are forward (positive sequence) and backward (negative sequence) voltages, respectively. The I_F and I_B are positive and negative sequence currents producing forward and backward torques respectively. The Z_F and Z_B are equivalent positive and negative sequence impedances at any slip s offered to I_F and I_B respectively. It is clear from the equation (1) that, any variation in the current due to single phasing and voltage unbalance will generate the pulsating torque, which is the reason for generating the radial vibration in the Induction motor. This vibration can be easily measured by using MEMS vibration sensor and used in identifying the faults.

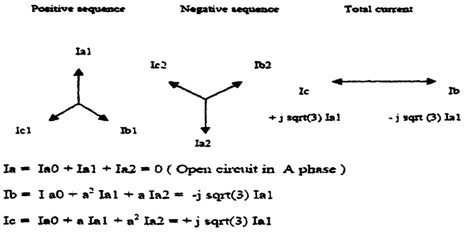

Fig.3. Sequence currents for open phase supply to motor.

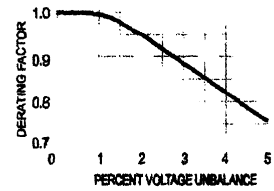

Fig. 4 – De-rating Factor from NEMA MGI

II. A.EFFECTS OF ELECTROMAGNETIC AND ELECTRONDYNAMIC FORCES IN INDUCTION MOTORS.

The electromagnetic forces acting in the alternating current motors (induction motors and synchronous motors) have their own peculiarities [8]. Primarily their frequency is twice the frequency of the magnetic field. This is because it is proportional to the magnitude of the magnetic field ignoring its direction. So the main electromagnetic forces in an alternating current machine are acting with the frequency $2f_m$, where f_m is the frequency of the supply voltage (a.c. mains). The second peculiarity is, by its magnitude, oscillating force has the slot frequency. The vibration with the slot frequency is sometimes traditionally called "magnetic noise". This vibration not always shows up visibly on the background of other components with nearby frequencies. There is a peculiarity of forming the oscillating forces defined by the slots of the rotor and stator. It consists in the fact that, the slots of the rotor enter the stator field with the frequency f_z=Z*RPM/60. But the field itself is a pulsating one, and can be resolved into two different components that rotate in opposite directions with the power-line (mains) frequency f_m. As there are two poles under which there are slots and the magnetic field has maximum magnitude, the forces act on three slot frequencies:

$$\left.\begin{array}{l} f_{z1} = Z*RPM/60 \\ f_{z2} = Z*RPM/60 - 2f_m \\ f_{z3} = Z*RPM/60 + 2f_m. \end{array}\right\} \rightarrow \qquad (2)$$

But the form of the stator oscillation has not so complicated form as the field has and respectfully the oscillation amplitude has an increased value only on one or two frequencies. It is defined by the machine construction, viz. by the number of poles and slots. When the rotor winding (squirrel cage) is absolutely symmetrical the electro dynamic forces have no alternating components. They generate only a constant (operating) torque. If the winding, i.e. the currents induced in it, is not symmetrical then a low frequency pulsating torque with a double slip frequency appears:

$$f_s=2Sf_m, \qquad (3)$$

Where S is the slip of the rotor that is equal

$$S = (f_m - p*RPM/60) / f_m.$$

Here p is the number of pole pairs. If the field of the stator is unsymmetrical, i.e. besides the field that rotates in the main direction with the frequency f_m, a badly compensated field that rotates in the opposite direction is present, and then there appears an alternating electro dynamic force and correspondingly a torque of forces with a frequency $2f_m$. This situation appears both when there are unsymmetrical stator windings and when the power-line is unsymmetrical. The theoretical background presented above to explain the causes of vibration in motor forms a basis in to explore the MEMS accelerometer based vibration measurement in detection of electrical abnormal conditions.

III. MEMS ACCELEROMETER FOR VIBRATION ANALYSIS: (ADXL202EB).

The ADXL202E [9] is MEMS technology based dual axis accelerometer on a single chip and has been designed by Analog devices Inc. USA. It contains a poly silicon surface micro machined sensor and signal conditioning circuitry to implement open loop acceleration measurement architecture. For each axis, an output circuit converts the analog signal to a duty cycle modulated (DCM) digital signal that can be decoded with a counter/timer port on a microprocessor. The ADXL202E has capability for shock/vibration sensing, categorized as iMEMS [Integrated MEMS] which doesn't need any external signal conditioning circuitry. The major benefits of ADXL202E are, it is a low-cost, low-power, complete 2-axis accelerometer with a measurement range of ± 2 g. The ADXL202 can measure both dynamic acceleration (e.g., vibration) and static acceleration (e.g., gravity). Since the ADXL202 is also sensitive to static acceleration, tilt sensing is also possible. Tilt sensing requires a very low noise floor which usually necessitates restricting the bandwidth of the accelerometer, while shock/vibration sensing explores wide bandwidth.

The output of the demodulator drives a duty cycle modulator (DCM) stage through a 32 k Ohm resistor. At this point a pin is available on each channel to allow the user to set the signal bandwidth of the device by adding a capacitor (C_X for X axis).

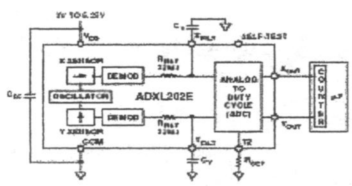

Fig.5. Block diagram of ADXL202 MEMS accelerometer

This filtering improves measurement resolution and helps prevent aliasing. After being low-pass filtered, the analog signal is converted to a duty cycle modulated signal by the DCM stage. A single resistor sets the period of DCM output. An analog output voltage can be obtained either by buffering the signal from the XFILT pin, for X axis or by passing the duty cycle signal through an RC filter, to set desired bandwidth. In the present application complete bandwidth is explored.

IV. EXPERIMENTAL SET UP USING MEMS ACCELEROMETER FOR VIBRATION ANALYSIS.

An experimental test set up was built as shown in fig. 6 & 7 for detection of single phasing and voltage unbalance conditions using vibration analysis & motor current signature analysis [MCSA] by suitably employing Hall Effect Current transducer. The test set-up for both methods consists of a 3 phase, 50Hz, 5 HP induction motor with brake drum load. The instrumentation includes MEMS accelerometer, a high resolution FFT analyzer, Hall Effect current transducer & a personal computer connected to FFT analyzer through RS232 cable. The motor name plate details are given in appendix –A. In order to obtain a better understanding of vibration modes of the motor and effects of the single phasing and voltage unbalance following experiment categories were examined.

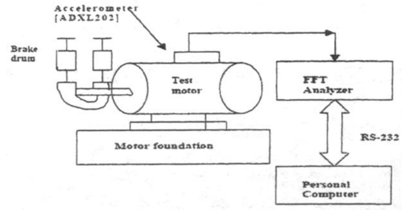

Fig.6 Experimental set up for vibration analysis using MEMS accelerometer.

Case 1: With rated voltage, rated speed, no load condition, no electrical faults, and healthy motor.
Case 2: With rated voltage, rated speed, no load condition, with single phasing.
Case 3: With rated voltage, rated speed, no load condition, with un balance voltage condition.
Case 4: With rated speed, load condition, healthy condition
Case 5: With rated speed, load condition, single phase condition.
Case 6: With Unbalance voltage, rated speed, load condition.

As an electrical machine stator exhibits mainly a radial vibration behavior [2], only the acceleration in the radial direction was measured in all the above experimental states.

IV.A EXPERIMENTAL SET-UP FOR MOTOR CURRENT SIGNATURE ANALYSIS [MCSA].

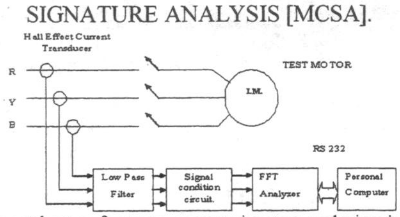

Fig.7.Experimental set up for motor current signature analysis using Hall Effect current transducer. (MCSA Technique)

V. EXPERIMENTAL RESULTS.

Case- 1: NO LOAD, HEALTHY CONDITION OF THE MOTOR.

[a] MEMS Accelerometer Output.

V=400V, N=1400, Ir=5.2A, Iy=4.2A, IB=4.6A; FFT SAMPLE RATE = 4 k SA /S, SPAN=1KHZ, SCALE =20dB.

Table -1: MEMS experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50	-36.88 dB	Funda : Funda	100
275	-36.88 dB	Funda : 275 Hz	100

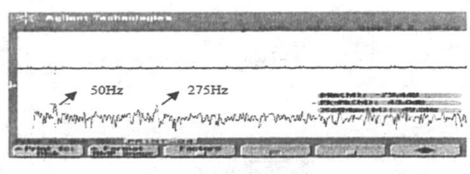

Fig: 8. FFT output of healthy motor, with 50Hz, 275Hz dominant.

[b] Hall Effect transducer Output (MCSA)

V=400V, N=1400, Ir=5.2, Iy=4.2, Ib=4.6A; FFT Sample rate = 4 k Sa /s , Span=1kHZ, Scale =20dB.

Table -2: MCSA experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50 HZ	-6.25 dB	Funda / Funda	100
150 HZ	-36..88 dB	Funda / 3rd	16.94
250 HZ	-34.38 dB	Funda / 5th	18.17
350 HZ	43.75 dB	Funda / 7th	14.28
450 HZ	-50.00 dB	Funda / 9th	12.[illegible]

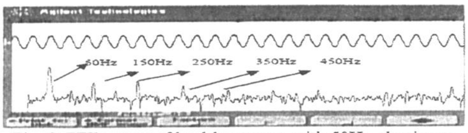

Fig: 9. FFT output of healthy motor, with 50Hz, dominant.

Case- 2: NO LOAD SINGLE PHASE CONDITION.

[a] MEMS Accelerometer Output.

V=400V, N=1400, Ir=5.2, Iy=4.2, Ib=4.6; FFT SAMPLE RATE = 4 k SA /S, SPAN=1KHZ, SCALE =20dB

Table – 3: MEMS experiment readings

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50	-36.88 dB	Funda / Funda	100
100	-38.13 dB	Funda / 100 Hz	96.72
275	-36.88 dB	Funda / 275 Hz	100

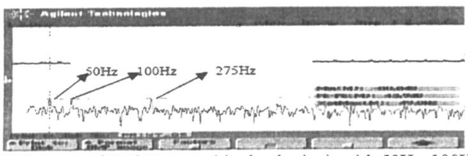

Fig: 10. FFT output of Faulty motor (single phasing), with 50Hz, 100Hz.275Hz component are dominant. (MEMS output)

[b] Hall Effect transducer Output (MCSA)

V=400V, N=1400, Ir=5.2A, Iy=4.2A, Ib=4.6A; FFT SAMPLE RATE = 4 k SA /S, SPAN=1KHZ, SCALE =20dB

Table -4: MCSA experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50 HZ	-6.25 dB	Funda / Funda	100
100 HZ	-43.7[illegible]dB	Funda / 2nd	10.01
250 HZ	-34.38 dB	Funda / 5th	18.17
350 HZ	-43.75 dB	Funda / 7th	14.28
450 HZ	-50.00 dB	Funda / 9th	12.5

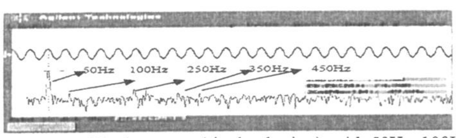

Fig: 11. FFT output of Faulty motor (single phasing), with 50Hz, 100Hz.250Hz, 275Hz, 350Hz, component are dominant.

Case- 3: VOLTAGE UNBALANCE CONDITION.

[a] MEMS Accelerometer Output

Vr = 180V ; Vy = 290V , Vb = 220V

Ir =5.2A ; Iy = 10.5 A , Ib = 6.2 A

Table -5 : MEMS experiment readings .

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50	-36.88 dB	Funda / Funda	100
100	-38.13 dB	Funda / 100 Hz	96.72
125	-49.06 dB	Funda / 125 Hz	76.45
275	-36.88 dB	Funda / 275 Hz	100

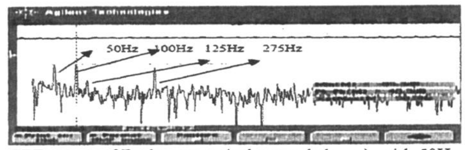

Fig: 12. FFT output of Faulty motor (voltage unbalance), with 50Hz, 100Hz. 125Hz, 275Hz, component are dominant. (MEMS output)

[b] Hall Effect transducer output (MCSA)

Vr = 180V ; Vy = 290V ; Vb = 220V

Ir =5.2A ; Iy = 10.5 A ; Ib = 6.2 A

Table -6: MCSA experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50 HZ	-6.25 dB	Funda / Funda	100
100 HZ	-40.0 dB	Funda / 2nd	3.125
150 HZ	-33.7dB	Funda / 3rd	3.70
250 HZ	-35.63 dB	Funda / 5th	3.50
350 HZ	-42.50 dB	Funda / 7th	2.94

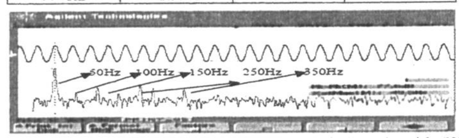

Fig: 13 FFT output of Faulty motor(voltage unbalance), with 50Hz, 100Hz.,125Hz,150Hz 275Hz,350Hz component are dominant.

Case- 4: LOADED & HEALTHY CONDITION OF MOTOR.

Ir =5.7A; Iy = 6.2 A; Ib = 6.0A

[a]. MEMS Accelerometer Output.

Table -7: MEMS Experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50	-36.88 dB	Funda / Funda	100
275	-36.88 dB	Funda . 275 Hz	100

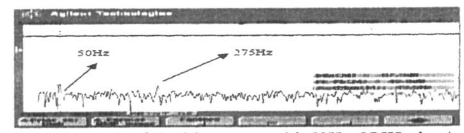

Fig: 14 FFT output of Healthy motor, with 50Hz, 275Hz dominant.

[b] Hall Effect transducer output (MCSA)

Ir =5.7A; Iy = 6.2 A; Ib = 6.0 A

Table -8 : MCSA Experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50 HZ	1.25 dB	Funda / Funda	100
250 HZ	-35.63 dB	Funda . 5th	3.50
350 HZ	-34.25 dB	Funda / 7th	3.64

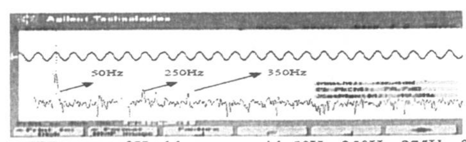

Fig: 15 FFT output of Healthy motor, with 50Hz, 250Hz, 275Hz, 350Hz component are dominant.

Case- 5: WITH LOAD SINGLE PHASE CONDITION.

[a] MEMS Accelerometer Output.

Ir =8A; Iy = 8.5 A; Ib =8. 6 A

Table -9: MEMS Experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50 HZ	-43.71 dB	Funda / Funda	100
100 HZ	- 45.88 dB	Funda / 100 Hz	95.27
275 HZ	-38.18 dB	Funda / 275 Hz	114.48

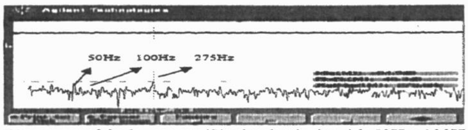

Fig:16. FFT output of faulty motor (Single phasing), with 50Hz, 100Hz, 275Hz, component are dominant.

[b] Hall Effect transducer Output (MCSA)

Ir =8A; Iy = 8.5 A; Ib =8. 6 A

Table -10: MCSA Experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50 HZ	-5 0 dB	Funda / Funda	100
100 HZ	-0dB	Funda / 2nd	0
150 HZ	-44.3dB	Funda / 3rd	11.20
250 HZ	-34.36 dB	Funda / 5th	14.55
350 HZ	-41.2 dB	Funda / 7th	12.13

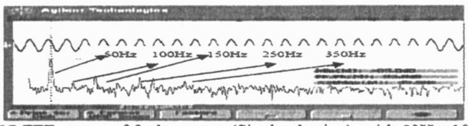

Fig: 17.FFT output of faulty motor (Single phasing), with 50Hz, 100Hz, 150Hz,250Hz,275Hz, component are dominant.

Case- 6: LOADED & BALANCED CONDITION

[a] MEMS Accelerometer Output

R	Y	B
200(86.9%)	200 (86.9%)	200 (86.9%)
Ir=8A	Iy=7.9A	Ib= 7.8ª

FFT SAMPLE RATE: 2 k Sa / S; Span: 1 kHz

Table-11: MEMS Experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50 HZ	-42.50 dB	Funda / Funda	100
275 HZ	-42.88 dB	Funda / 275 Hz	99.11

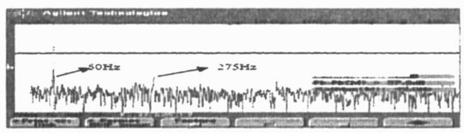

Fig: 18. FFT output of motor (Balanced voltage), with 50Hz, 275Hz, component are dominant. (MEMS output)

[b] Hall Effect transducer Output (MCSA)

R	Y	B
200(86.9%)	200 (86.9%)	200 (86.9%)
Ir=8A	Iy=7.9A	Ib= 7.8A

FFT SAMPLE RATE: 2 k Sa / S; Span: 1 kHz

Table-12: MCSA Experiment readings.

Harmonic In Hz	Amplitude in dB	Ratio in Percentage	
50 HZ	-1.88 dB	Funda / Funda	100
250 HZ	-42 50dB	Funda / 3rd	4.42
275 HZ	-39.7 dB	Funda 5th	4.73
350 HZ	-43.75 dB	Funda / 7th	4.29

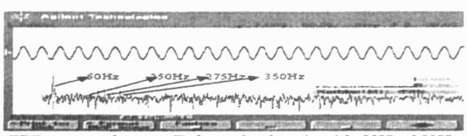

Fig: 19. FFT output of motor (Balanced voltage), with 50Hz, 250Hz, 275Hz, 350Hzcomponent are dominant.

Inferences of the above said cases as follows.

Referring to case 1& 4, it is clear from both methods that a healthy motor irrespective of load or no load, 50Hz component with 275Hz sub-harmonic component exists. *Referring to case 2 & 5,* with load & no load single phasing situation, it is clear from both methods that fundamental and 100Hz component are dominant, other components with negligible magnitudes. This shows that a negative sequence current with 2f frequency causing bad effects to motor health. *Referring to case 3 & 6*, under no load & loaded un -balanced voltage condition; it is observed that dominant presence of 100Hz and 125Hz component along with 50Hz component. This shows a negative sequence of current with 2f frequency, causing bad effects on motor. The amplitude of the 125Hz component varies, depending on percentage of unbalance in voltage. The 275Hz component depicts the variation of reluctance in the slots, which has no harm effect on motor.

VI. BENEFITS OF PROPOSED MEMS ACCELEROMETER BASED VIBRATION ANALYSIS METHOD OVER CONVENTIONAL METHOD.

The proposed method has following advantages over conventional MCSA method for detection of phase unbalances conditions.

1. It is a non electrical contact type method which is free from electrical hazards.
2. It makes use of MEMS accelerometer which is a low cost, reliable and compact. They are more flexible because of bi-axial (both X and Y direction) vibration measurement.
4. MEMS accelerometers are light in weight, compact in size and consume low power.
5. Resolution is superior when compared conventional accelerometers.
6. The cost of the instrument becomes very cheap with the usage of MEMS accelerometer.
7. No CT saturation problems, which is there in Hall effect current transducers.

VII. CONCLUSION.

Two methods of fault diagnosis viz. Vibration analysis and Current signature analysis have been analyzed on their ability to detect induction motor operation abnormalities. The detection of electrical abnormalities through vibration analysis is more beneficial when compared to MCSA, as it is non electrical contact type measurement. The vibration analysis using MEMS accelerometer is less expensive compared to conventional methods (US $250 to US $25). It is to detect supply unbalance, single phasing and electrical faults, which does not require any skilled engineer. The vibration analysis using MEMS transducers may also be extended to detect mechanical faults in stator and rotor such as rotor bar damage, end ring damage, rotor unbalance, misalignment, air gap eccentricity, looseness in stator wedges, and foundation looseness. Presently research work is in progress to explore these detection techniques using various MEMS transducers.

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Appendix – A: Name Plate Details of Test Motor.

Name	: 3Ph Induction Motor
Freq	: 50 Hz
Voltage	400 – 440 v
Rating	: 5 HP
Current	8A
Speed	1440 rpm.