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International Journal for Modern Trends in Science and Technology, 8(05):571-578, 2022
Copyright © 2022 International Journal for Modern Trends in Science and Technology
ISSN: 2455-3778 online
DOI: https://doi.org/10.46501/IJMTST0805087
Available online at: http://www.ijmtst.com/vol8issue05.html

Important Discovery of Stator Winding Inter-Turn Insulation Degradation for Condition Monitoring of Induction Motor using Non-Invasive System by Vibration Analysis

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To Cite this Article
Satyanarayana Rao R.D and K.S Aprameya. Important Discovery of Stator Winding Inter-Turn Insulation Degradation for Condition Monitoring of Induction Motor using Non-Invasive System by Vibration Analysis. International Journal for Modern Trends in Science and Technology 2022, 8(05), pp. 571-578. https://doi.org/10.46501/IJMTST0805087

Article Info
Received: 22 April 2022; Accepted: 12 May 2022; Published: 26 May 2022.

ABSTRACT

In view, of the modern control structure of present industrial needs, the induction motor has become a natural mechanical workforce in every lower to higher end process operation. It encounters several electrical and mechanical faults while improving its performance structure. This paper focuses on stator winding inter-turn insulation degradation discovery of three- phase squirrel cage induction motor for non-invasive system by vibration analysis. Motor current signature analysis (MCSA) is one of the best techniques where the current spectrum is analyzed with spectral analysis using Fast Fourier transform (FFT). Using this MCSA based online method can overcome the problems of single phasing, voltage unbalancing, etc., Due to stator winding inter-turn insulation degradation, which automatically produces rotor slot harmonics, giving rise to broken rotor bar faults and mixed eccentricity faults. Theoretical analysis and experimental results of electrical & mechanical faults are analyzed using motor current signature analysis with vibration analysis.

KEYWORDS: Induction motors, Inter- turn insulation degradation, Condition monitoring, Motor current signature analysis, Vibration analysis.

1. INTRODUCTION

Induction motors are termed as the traditional workforce of any industry due to their less investment, rugged construction, with reliable performance. Due to its challenging and reliable nature, faults in them are unavoidable. The most frequently introduced faults are single phasing, the unbalanced voltage on the supply side, inter-turn short circuit, and some mechanical faults of air gap eccentricity, broken rotor bar, and bearing fault on the motor side.

Swapnil k. Gundewar [1], specifies that in every industrial process, nearby 90% of the machines are termed as induction motors working as a prime mover. The vibration monitoring methodologies support effectively identifies mechanical faults such as bearing defects and rotor- stator hub.

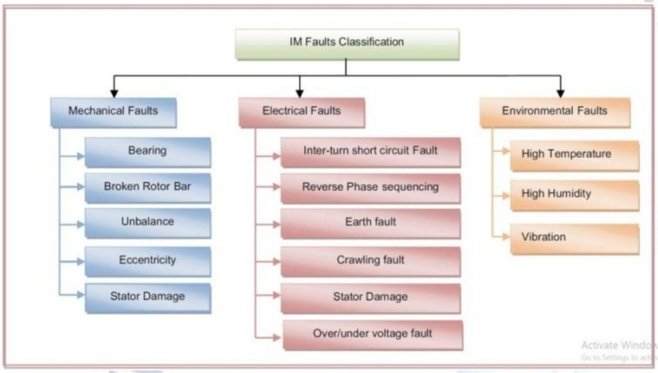

Fig 1. Induction motor Faults classification based on Swapnil k. Gundewar et al.[1], Journal of Vibration Engg.,& Technologies.,2020.

P.Popaleny, J [2], introduced fast Fourier transform applicable to motor current signature analysis based on analyzing the current demanded by the machine during steady-state operation. To detect faults in squirrel cage Induction motors, vibration Analysis with Current Analysis is commonly used. In the view of mechanical faults detection, Vibration Analysis has been employed.
Dayong Zheng and Pinjia zhang [3] have explained that to avoid catastrophic insulation failure in induction motor, stator winding fault detection system is used. So condition monitoring systems can monitor the health condition of stator insulation are developed.
Israel Zamudio-Ramirez et.al [4] presents flux-based methods for recent technological contributions related to the development and application of the monitoring of rotating electric machines.
Konstantinos N. Gyftakis [5], explained that the turn-to-turn faults that occurred in the induction motors are one of the most necessary motor failures to detect online and also at incipient situations. Akash C. babu and Jeevanand Seshadrinath [6], give a multiple coupled circuit of a three-phase squirrel cage induction motor based model on exact stator winding layout, skewing of rotor bars, and the linear rise in the stator slot mmf, consolidating the space harmonics associated within the fault.
Shubhasish Sarkar et.al [7], introducing a new method called NI-Compact RIO-based online stator winding fault identification method for proper discovery of partial degradation and stator winding insulation failure.Isabela Oliveira zaparoli et.al [8], initiates an inter-turn short circuit of the stator winding is a very critical failure because its turns to the least condition suddenly. So, the initial identification of the inter-turn short circuit is of primary importance to come out from substantial damage to the motor.

Regular testing of the stator winding insulation, which is the most important component in medium voltage motors mentioned in H.Kim et al. [9], also this predictive maintenance is a necessary part for preventing unplanned reduction in the capability of power generation.S. Das et al. [11] discussed a method for differentiation of stator winding severe short circuit conditions with medium short circuit conditions. Due to the nature of unbalanced supply voltage, the current also varies. In the view of unbalanced currents or voltages, there is a differentiation in motor asymmetry that makes negative sequence current.

Peter Nussbaumer et al. [12], have discussed the proper state of insulation in off-line mode by analyzing a transient reaction with respect to voltage step excitation. Witold Pawlus et al. [13], have initiated a methodology to find three-phase induction machines insulation degradation by using two current sensors. Here current transients are evaluated using step excitation.S.M. Nawazish Ali et al. [14], introduce the thermal effects on the electric motor combination. This collective information is helpful for the researchers in developing of various analogies.

Malgorzata Sumislawska et al. [15], have discussed thermal aging impact on electrical properties of winding insulation thin-film. Here parameters of equivalent-circuit model measurements are considered by taking suitable samples. Aldo Boglietti et al. [16], introduce high-frequency properties evaluation connected to changes in the insulation health state of the machine. Due to this high-frequency properties influence, there is a gradual change in insulation capacity terns to major deterioration.

Wiltold Pawlus et al. [17], present the first-order thermal model relationship with loadability curves of induction motor by frequency driven nature. By using these loadability curves, major parameters of a thermal model are identified.Stefan grubic et al. [18], discussed monitoring and testing techniques of turn-to-turn insulation degradation toward condition monitoring of low-voltage induction machines. These monitoring and testing techniques are interesting topics in the present situation in industrial aspects.

Sang Bin Lee et al. [19], introduced the terminal box concept to assess the insulation condition of the motor in the non-invasive manner by measuring the differential leakage currents of each phase winding. Here high performance current sensors are implemented with higher accuracy leakage currents.Sang Bin Lee et al [20] have discussed the ground wall and phase-to-phase insulation condition monitoring technique of a three-phase induction motor. Here dissipation factor (tan δ), capacitance, and ac insulation resistance indicators of insulation condition are calculated online by measuring differential leakage-current.

Majid Malekpour, B.T et al [21] have identified inter-turn faults in turns or coils of stator winding. These precautionary measures are taken by the manufacturer during the assembly of winding and inter-turn insulation withstands the capacity of impulse voltage.Puranik K.K [22] discussed the concepts of the stator winding insulation system of the lifetime of high voltage electrical machines. For different types of high voltage electrical machines and transformers different techniques of insulation resistance, insulation testing, and polarization index are verified.

By studying above Literature survey, that the research works are focused mainly to different load torque conditions for healthy and faulty motor with fault specific harmonics for various methods. These harmonics are arising due to stator inter turn shorts and mainly voltage unbalance in the three phase supply, losses in the rotor slot harmonics, static or dynamic eccentricities. In the view of these phenomena's, there is gradual degradation of machine insulation towards abnormal thermal, mechanical, electrical and environmental stresses. In this direction, present work is mainly focused on stator winding insulation degradation detection using non-invasive method by vibration analysis.

2. CHARACTERISTIC FREQUENCIES FOR MOST COMMON FAULTS IN INDUCTION MOTORS

A. Single Phase Fault:

The appearance of $2f_s$ frequency component in a vibration spectrum gives nature of single phase fault in induction motor, where f_s = supply voltage frequency in Hz [3].

B. Unbalance Voltage Fault:

Due to supply voltage unbalancing, vibration spectrum sidebands of the induction motor frequencies are [1]

$$f_{UBV} = (1+2.k).f_s \quad (1)$$

Where k= 1, 2, 3…, $k \in \mathbb{N}$; f_{UBV}= Unbalance supply voltage frequency; fs = supply frequency. The appearance of 3fs, 5fs, 7fs and so on, harmonic components in vibration spectrum is a clear indicator of unbalance voltage condition.

C. Rotor Bar Damage Fault:

Rotor failure is another important fault that is frequently found in IM, which turns fault current flows in rotor circuit. The damaged rotor bars will induces harmonic components in the stator current or vibration spectrum at frequencies given by [7, 8].

$$f_{br} = (1 \pm 2ks)\, f_s \quad (2)$$

Where f_{br} = broken rotor bar frequency in Hz; k = 1, 2, 3... Integers, s = slip and f_s= supply frequency. The upper side band $(1+2s)f_s$ is due to consequent speed oscillations, while the lower side band $(1-2s)f_s$ is fault related.

A.Air gap Eccentricity Fault:

Air gap eccentricity is another fault found in IM. It is caused by the formation of unmatched air gap with respect to stator and rotor. They exist in the form of static eccentricity and dynamic eccentricity or presence of both termed as mixed eccentricity [6]

$$f_{mix} = (f_s \pm k.f_r) \quad (3)$$

Where k=1, 2, 3…. and

$$f_r = \frac{(1-s)}{p}.f_s \text{ Hz} \quad (4)$$

3. DIFFERENCE BETWEEN MOTOR CURRENT SIGNATURE ANALYSIS Vs VIBRATION ANALYSIS.

Motor Current Signature analysis is one of the best desirable and generally used fault detection method. Here fault harmonics are determined as fault indications by analyzing current spectrum of the motor. But current analysis with vibration analysis is generally used to detect faults in squirrel cage induction motors. For mechanical faults, vibration analysis is best suitable detection method.

During steady state operation, this motor current signature analysis is analyzed by using fast Fourier transform by taking reference of current signals. In general, additional harmonic components are introduced in winding as well as principle slot.

These winding harmonics are produced by harmonic presence in supply voltage and distribution of conductors in the stator perimeter. Due to this nature air gap field is not sinusoidal one.

Several fault components are amplified during certain fault in the presence of current and vibration spectra. For detecting both electrical and mechanical faults, vibration analysis also used with motor current signature analysis. However, various faults can generate different harmonics. Stator winding faults relates to certain harmonics.

The stator inter-turn fault indication given by equation (5)[10].

$$f_{stator} = f\left\{\frac{n}{p}(1-s) \pm k\right\} \quad (5)$$

This stator inter-turn fault produces rotor slot harmonics as in equation (6) [9].

$$f_{sh} = \left(1 \pm \left(\lambda \frac{R}{P}(1-s)\right)\right) f_1 \quad (6)$$

Where λ=1, 2, 3…., R is the no. of rotor bars, p is the total no. of poles/2, s is the slip and f1 fundamental supply frequency.

The rotor broken bar fault indicators are computed using equation (7)[9].

$$f_{broken} = f(1 \pm 2s) \quad (7)$$

The static eccentricity fault indicators are given by equation (8) [9].

$$f_{static} = f\left\{R\left(\frac{1-s}{p}\right) \pm k\right\} \quad (8)$$

The dynamic eccentricity fault indicators are given by equation (9)[9].

$$f_{dynamic} = f\left\{\left(R \pm n_d\right)\left(\frac{1-s}{p}\right) \pm k\right\} \quad (9)$$

The constant electromagnetic torque [10] can be produced if the two magneto motive force (mmf) waves Fs (stator mmf) and Fr (rotor mmf) are stationary with respect to each other.

Te = -P/2 .K. Fs. Fr. Sinδ (10)

Te=Electromagnetic torque, P=No. of poles, Fs= stator mmf, Fr= rotor mmf wave, K= Constant obtained by machine dimension, δ=Rotor displacement angle, negative sign indicates the electromagnetic torque take measures in a direction so that magnetic fields of stator and rotor into same sequence.

4. EXPERIMENTAL SETUP

The present work uses a non-invasive method to observe the electrical and mechanical abnormalities of induction motor. It is a simple method to make use of 3 Phase LEM-CTSR 0.6-P - Hall effect current transducer is introduced from incoming 3 phase supply from the output side of the auto- transformer to three lines to induction motor. The better signature of healthy and faulty conditions of the motor also found by using Fast Fourier Transform algorithm for Vibrations setup in the motor. During its preliminary work, Tektronics 70 MHZ, 1 Giga samples/sec digital oscilloscope contains default FFT analysis, is made use. By setting FFT option, it can be used to capture and save the signals in the memory of the oscilloscope. Later it can be downloaded to the personnel computer using an RS-232 communication cable.

An experimental setup of present work is observed in below Fig 2 for the detection of the stator winding insulation degradation of motor such as normal running with various loadings such as no-load, half load, and full load conditions using Motor current signature analysis and Vibration analysis. The test setup which consists of motor-1, a 3 phase,50Hz,1.5hp,1415rpm,400V squirrel cage induction motor with mechanically loaded brake drum,and motor-2,a 3 phase,50Hz,1.5hp,1400rpm,400V squirrel cage induction motor with mechanically loaded brake drum. The instrumentation for both Current and Vibration analysis includes 3 Phase LEM-CTSR 0.6-P with PCB & Connector, 0-10A Input, 0-5V Output, Hall Effect current transducer, a high- resolution digital oscilloscope with a personnel computer connected through an RS-232 communication cable.

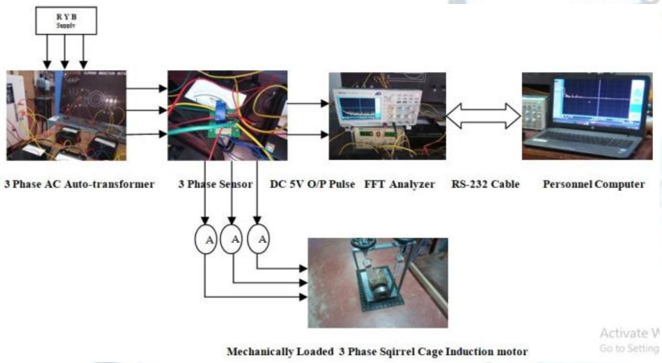

Fig: 2 Schematic of the Experimental setup

Motor Specifications	Motor-1	Motor-2
Performance Frame & make	IS/IEC 60034 ,Crompton Greaves	IS/ 375, Vinayaka Electricals,B'lore.
K.W(H.P)	1.10(1.50)	1.10(1.50)
Voltage	415±10%	415
RPM	1415	1400
Insulation class	F	B
HZ	50±5%	50
A	2.55	2
Efficiency Full load	78.00	76.00

Table 1. Motor Specifications.

Fig: 3 Experimental setup used in the laboratory

5. RESULTS AND DISCUSSIONS

A. Under No load & healthy condition:

A healthy induction motor working on balanced 3 phase supply, motor gives uniform & accurate running. The spectral analysis of motor during healthy condition and faulty motor stator winding inter turn degraded condition during no load is shown in fig 4 of FFT analyzer and Mat lab output. It shows dominant fundamental frequency component f_s only at 49.81Hz and -3.79dB, due to the distortion in the measurement which is allowable limit. This is clear sign of healthy motor. But by analyzing faulty condition, motor draws more current resulting in excessive heat due to losses in stator & rotor.

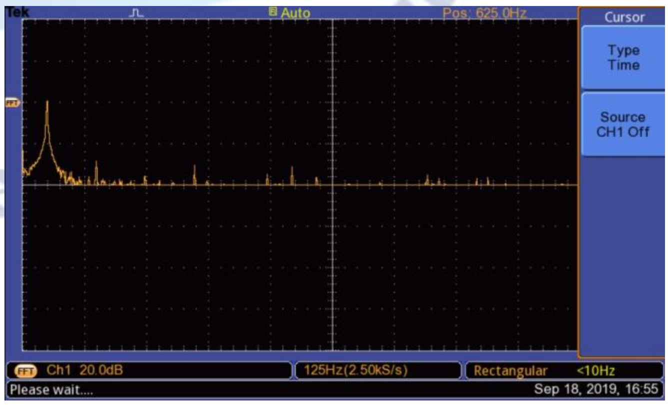

Fig.4 Motor 1- No load normal condition - FFT analyzer output

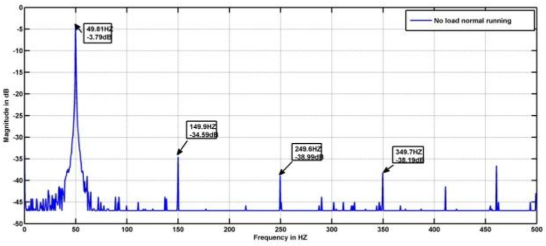

Fig.5 Motor 1- No load normal condition – Mat lab output

B. Half load condition:

By applying suitable half load to faulty motor, it turns to decrease in speed and rise in current magnitude. The voltage unbalance condition also observed. It is found that increase in slight vibration, humming nature, motor temperature as differentiate to no load condition. Fig 6 and 7 exhibits the Motor 2- Half load normal condition - FFT analyzer output and Mat lab output.

It is observed that nearby the equality of frequency components appeared as analyzed with no load spectrum of the motor.

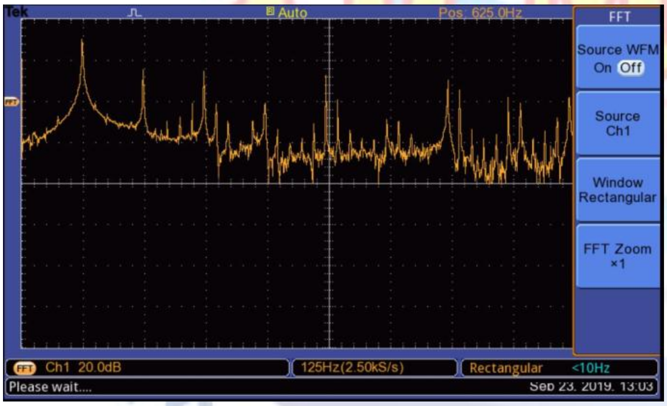

Fig.6 Motor 2- Half load normal condition - FFT analyzer output

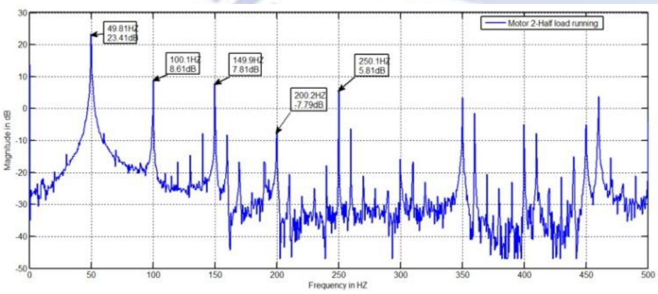

Fig.7 Motor 2- Half load normal condition – Mat lab output.

C. Full load condition:

During full load condition, as we know there is a further limit in speed and a considerable rise in magnitude of current. By observing unbalanced voltage, and more humming sound and higher vibrations and noise conditions are reached. The FFT analysis of motor under this nature is shown in fig 8, which gives the comparison of FFT spectrum of stator winding faulty motor during 10% & 20% full load condition.

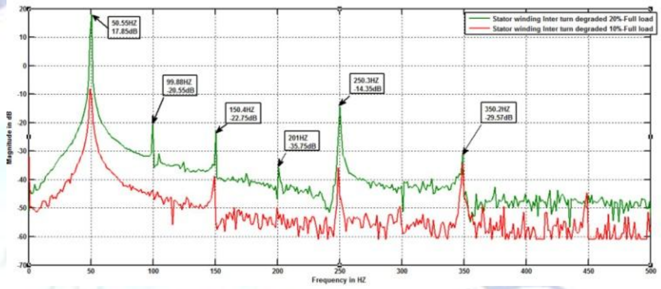

Fig.8 Comparison of FFT spectrum of Stator winding faulty motor during 10% & 20% full load condition.

6. INVESTIGATION ON ELECTRICAL FAULTS

A Single phase condition:

Experiment has been conducted on motor-1 with one of supply terminal disconnected suddenly during running condition. The vibrations developed in the motor due to single phase fault have been captured by current signatures. The spectral analysis of vibration signal by FFT algorithm shows the existence of 2fs, 3fs and 5fs components. Fig.9 provides the comparison of FFT analyzer results and that of proposed system for single phase fault with motor 1 & 2.

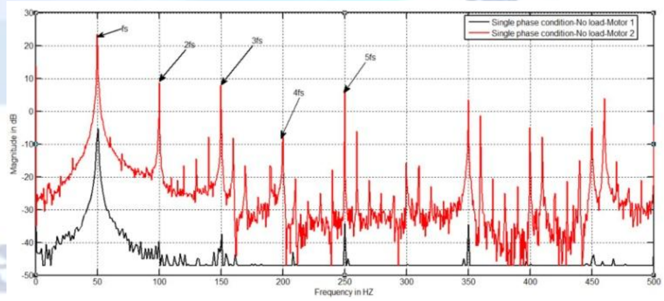

Fig.9 Comparison of FFT analyser results for single phase fault with motor 1 & 2.

B Unbalance Voltage Condition:

When an IM operates under unbalance voltage condition, the circulation of negative sequence currents will gives rise to oscillating torque. As a result there is increase in motor vibration, temperature rise and reduction in speed. The vibration produced in motor due to unbalance voltage has been captured by current signatures. The spectral analysis of vibration signal by FFT algorithm shows the appearance of 3fs, 5fs and 7fs frequency components. These components can be used as indication of unbalance voltage condition. Referring to Eqn.(1), for k = 1,2,3 so on, it gives theoretical fault frequency f_{ubv} = 3fs, 5fs,7fs and so on. Fig.10 provides the comparison of FFT analyser results and that of proposed system for unbalance voltage condition with motor 1 & 2.

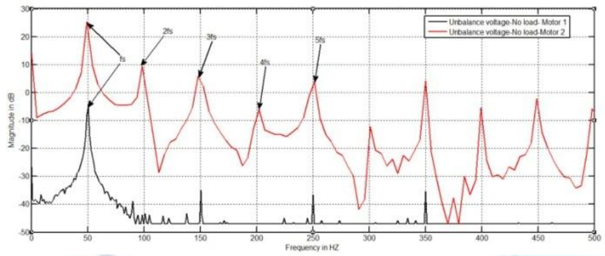

Fig.10 comparison of FFT analyser results for unbalance voltage condition with motor 1 & 2.

C Broken Rotor Bar:

The IMs working in cement, iron and steel, tyre manufacturing, coffee curing, paper industries, stone crushing plant etc., are related to maximum permissible limits of electrical, mechanical, thermal and environmental stresses, belongs to the repeated starts and stops under various load conditions. This will lead to abnormal current flow, electrical & mechanical stresses in rotor circuit leading to rotor bar damage.

In the present work, experiment has been conducted on a faulty motor with one broken rotor bar under no load condition. The vibration produced under this condition has been captured by proper signatures. The spectral analysis shows side band frequency components. The left hand side band *(1-2ks)fs* exists due to rotor asymmetry and the other right hand sideband *(1+2ks)fs* sideband frequency components exists because of speed fluctuation. Fig.11 provides the comparison of FFT analyzer output for broken rotor bar condition with motor 1 & 2.

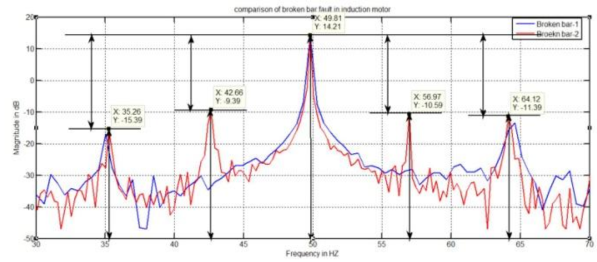

Fig.11 comparison of FFT analyser results of broken rotor bar situation with motor 1 & 2.

7. CONCLUSION

Comparison of results of the motor under healthy and faulty motor stator winding inter-turn degraded condition during no load is shown. It shows a dominant fundamental frequency component f_s only at 49.81Hz and -3.79dB, due to the distortion in the measurement which is allowable limit. This shows a better indication of the healthy motor. A curve gives a clear indication of the faulty motor during no-load, half load & full load conditions. The vibrations developed in the motor due to single phase fault have been captured by current signatures. The spectral analysis of vibration signal by FFT algorithm shows the existence of 2fs, 3fs and 5fs components in single phase fault. The spectral analysis of vibration signal by FFT algorithm shows the appearance of *3fs, 5fs* and *7fs* frequency components in unbalance voltage condition. Similarly, the spectral analysis of broken rotor bars shows side band frequency components. The left hand side band *(1-2ks)fs* exists due to rotor asymmetry and the other right hand sideband *(1+2ks)fs* sideband frequency components exists because of speed fluctuation. Fig 8 gives the comparison of FFT spectrum of stator winding faulty motor during 10% & 20% full load condition.

ACKNOWLEDGEMENTS

The author gives thanks for this work supported by the Electrical & Electronics department, U.B.D.T College of Engineering, Davanagere & also the Electrical & Electronics department, Adichunchanagiri Institute of Technology, Chikkamagaluru, Karnataka, India.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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