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Unbalanced Voltage Detection with Measurement Current Signature Analysis (MCSA) in 3-Phase Induction Motor Using Fast Fourier Transform (FFT)

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***Abstract*— This paper presents a computational tool for detecting unbalanced voltage supplies in induction motors. For real-time applications, a technique based on the Fast Fourier Transform (FFT) was used to compute the desired component frequency. A Labview virtual instrument was used to implement the computer algorithm. When supply voltage unbalance appears identical, fault diagnosis using current signature analysis becomes more difficult. The detection percentage is calculated in the following conditions: balanced voltage, under voltage (10%), over voltage (5%), and mixed voltage (UV 5% + OV 5%). The unbalanced voltage waveforms are then analyzed using the classical Fast Fourier Transform (FFT). The results were detected at frequencies of 25 Hz and 75 Hz with a high amplitude of -30 db, when compared with healthy conditions at this frequency there was no spike in amplitude values. So by using the MCSA method with the fast Fourier transform approach analysis, it was successful in detecting voltage unbalance disturbances in 3 phase induction motors.**

***Keywords*—3-Phase Induction Motor, Fast Fourier Transform (FFT), MCSA, Unbalanced Voltage.**

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I. Introduction

Induction motors are the most adaptable electrical machines found in an industrial setting. These are typically linked to a process system or any equipment to power the entire system. According to one study, the performance of an induction motor in a process system has a direct impact on business. Induction motors are extremely durable and efficient in operation. However, factors such as duty time, installation errors, environmental factors, and improper maintenance all contribute to a motor's failure rate, resulting in unscheduled breakdown and production loss. As a result, monitoring and maintaining an induction motor is a critical task performed by a maintenance engineer [1],[2]. One of the methods used in predictive maintenance uses current signature analysis method to detect unbalanced voltage. The detection of electrical signals containing a direct current component is known as current signature analysis.

Current signature analysis may be utilized in any industry that uses induction motors to do non-intrusive online (or remote) study of current motorized systems. It supplies and identifies mistakes while the motors are still operational, without interfering with service. This may be utilized efficiently to detect and locate a variety of motor operating faults [3]-[5]. The two most common approaches for identifying imbalanced voltage in motor induction are current signature analysis and vibration analysis on motors. A research on an induction motor to evaluate the influence of an imbalanced voltage on defect detection using a current signature is currently available for evaluation [6]. Unbalanced supply voltage has a negative impact on electrical devices, especially motors. Asymmetrical transformer winding, unbalanced loads, or excessive single-phase loads can all produce voltage imbalance in the supply. Despite the tiny voltage imbalance, a substantial unbalanced current flows due to the low negative sequence impedance. This high current produces heating, higher losses, vibrations, acoustic noise, torque loss, and shortens the life of an induction motor [7], [8].

All available solutions are intrusive in operation (requires a shutdown period for testing), necessitate measuring equipment maintenance, require a significant initial capital investment, are extremely sensitive and unreliable sources with even minor unsuitable environmental factors, and are slower in fault detection. All of the shortcomings of the previous approaches merged to create current signature analysis an irrefutable, feasible, trustworthy, and superior option for defect detection mechanisms to be employed in even small-scale companies. They are widely employed in a variety of settings because to their non-intrusive approach to problem detection and a quick identification method based on Fast Fourier Transform (FFT) analysis [9],[10]. Normally current signature are performed with Fast Fourier Transform analysis which is effective in cases of constant load but as of today it is being an emergent problem to find fault in changing and fluctuating load conditions. This study will look at detecting supply voltage imbalances on a three-phase induction motor.

There are several methods for analyzing current signatures. Basically, this experiment involves looking at the steady-state current spectrum to analyze the unbalanced supply voltage on a three-phase induction motor. The performance of the induction motor can be observed by following this procedure.

II. RELATED RESEARCH

Several studies related to fault detection methods in 3-phase induction motors have been applied. In Adhitya's research [11], by conducting failure detection experiments on the rotor bar of an induction motor, it affects the resulting stator current, through a stator current signal approach to detect F_{sb} (Side Band Frequency) around the source terminal, we will obtain phase characteristics that represent the frequency performance of the motor as a whole. real time. The analysis process was carried out on the phases obtained using the MCSA (Motor Current Signature Analysis) method. MCSA is a collection of diagnostic techniques for analyzing current waveforms that are able to detect failures in induction motors. Several diagnostic techniques that have been used include: FFT (Fast Fourier Transform), STFT (Short Time Fourier Transform), and Wavelet Transform. By approaching the phase characteristics with the FFT diagnostic technique. The analysis results from using this technique show an increase in the amount of energy in each frequency band range, so that the condition of the motor can be known whether it is normal or whether there is damage.

According to Zainal [12], a 3-phase induction motor stator disturbance results in an increase in the current value when a disturbance occurs in one of the phases, and the increase in current value is directly proportional to the percentage of the number of disturbances that occur. The increase in temperature value in the faulted winding increases more quickly when a stator fault occurs and there is a difference in temperature value between the normal winding and the faulted winding. Stator disturbances also affect the slip value of 3 phase induction motors where the slip value increases when a disturbance occurs, as well as the motor torque value increasing when the stator experiences disturbances, the increase in slip and torque values looks significant when the motor is under load. The difference in the current FFT wave spectrum is very visible between normal and disturbed motor conditions, the frequency noise in the signal produced in the FFT wave spectrum increases and the noise value in each test increases along with the increase in the percentage of damage to the stator of the 3-phase induction motor. So from several related references, an experiment was carried out to detect voltage source imbalance in a 3-phase induction motor using the MCSA method through Fast Fourier Transform (FFT) analysis. So that this failure can be prevented even though safety has been provided in the form of a phase failure relay.

Numerous successful strategies have been presented for detection utilizing the MCSA principle. Rangel Magdaleno et al. [13], [14] used the expansion operation in mathematical morphology to analyze the current signal, increasing the detection target and successfully recognizing damaged rotor bars under steady-state circumstances. Rivera Guillen et al. [15] used spectral subtraction to successfully decrease the supply frequency and noise after conducting an FFT on the motor startup transient current output.

Drif and Marques Cardoso [16] used the spectrum of instantaneous active power and instantaneous reactive power to distinguish between inter-turn short circuits and static eccentricity, followed by the spectrum of stator voltage modulus to distinguish between voltage imbalance and inter-turn short circuits. To anticipate impending defects, Allal and Khechekhouche [17] developed the motor current normalized residual harmonic analysis approach. This approach comprises linearly normalizing the current signal under both healthy and defective situations, followed by spectral subtraction to provide fault indicators for identifying broken rotor bars and inter-turn short circuits in stator windings.

In time-frequency analysis using a window, raising the sampling frequency increases time resolution, while extending the sampling length improves frequency resolution. When the signal-to-noise ratio is poor, an increase in sampling frequency is required to collect enough fault information. Furthermore, great frequency resolution is essential. However, obtaining high temporal resolution and high frequency resolution at the same time is unfeasible due to the huge computational load. To overcome this issue, the wavelet transform's changeable time localization and frequency resolution provide an adaptive windowing function appropriate for evaluating nonstationary data. Both MCSA-CWT [18],[19] and MCSA-DWT [20],[21] have been used to identify motor problems from current signals under nonstationary situations.

However, wavelet transformations iteratively breakdown low-frequency approximation signals but do not analyze high-frequency detail signals. As a result, they provide improved time localization but reduced frequency resolution for high-frequency harmonics. The proposed MCSA-based wavelet packet decomposition (MCSA-WPD) improves frequency resolution for high-frequency harmonics. Teotrakool et al. [23] used a second-order notch filter to suppress the fundamental harmonic of the current signal in order to identify ball-bearing flaws at varied speeds. MCSA-WPD was then implemented as a two-channel filter bank with consecutive filtering and down sampling, enabling for the wavelet packet coefficient to match to the fault frequency band.

III. RESEARCH METHOD

A. Unbalanced Voltage Fault

The quality of incoming electric power is one of the factors influencing the voltage and frequency that exist in induction motor performance. Motor imbalances caused by one of the different phases can be detrimental to the induction motor performance. The voltage in each phase of a three-phase system must be the same magnitude, symmetrical, and at a 120° angle [24]. The National Electrical Manufacturers Association (NEMA) and the International Electrotechnical Commission (IEC) introduced voltage imbalance definitions, one of which was used to analyze the electrical machine [25]. According to the NEMA definition, the percentage imbalance voltage (VUP) in the engine terminal can be expressed as

$$VUP = \frac{\Delta VMax}{average\ voltage} \times 100\% \quad (1)$$

The unbalance voltage is defined by The IEEE through the phase voltage unbalance rate (PVUR), which is given by equation (2) [26].

$$VUR = \frac{Max\ voltage\ deviation\ from\ avg.phase\ voltage}{Average\ phase\ voltage} \quad (2)$$

The IEC has explained the imbalance voltage as the ratio between the reverse voltage component and the positive voltage component. The percentage of Voltage Unbalance Factor (VUF) is given by equation (3) [27].

$$VUR = \frac{Negative\ sequence\ voltage\ component}{Positive\ sequence\ voltage\ component} \quad (3)$$

Unbalanced supply voltage to the induction motor can degrade motor performance as well as shorten the induction motor's life. A small amount of voltage unbalance can cause large current unbalances in the motor, resulting in temperature rise and, ultimately, insulation failure [28].

B. Fast Fourier Transform (FFT) Methods

Detection of faults in induction motors generally by using machine vibration analysis or harmonic analysis, Fast Fourier Transform (FFT) is a technique that is widely used for stationary signal analysis. The fast fourier transform of the signal $x(f)$ in time is given by [29]:

$$x(f) \int_{-\infty}^{+\infty} x(t) e^{-j2\pi f t} dt \quad (2)$$

The fast fourier transform analysis is used principally to describe a temporal signal in the frequency domain with a constant frequency resolution on a linear frequency scale.

C. Current Signature Analysis

The current signature analysis is a monitoring approach for three-phase induction motors that examines the current flowing through the stator winding [30]. The current signature analysis technique involves taking current from the winding stator using a sensor from the current transformer in the current probe, then analyzing and storing the data in NI 9246 as a signal; if a disruption occurs, the data is evaluated again using Matlab software [31].

Figure 2 shows the current signature analysis technique, which involves obtaining current from the winding stator using sensors from the current transformer within the NI 9246, then analyzing and temporarily storing the data in Labview; if there is a disruption, the data is studied in Matlab.

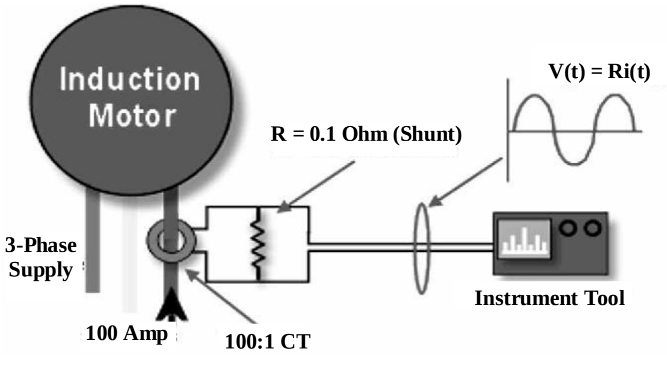


Figure 1. Current signature analysis procedure [32]

A 3-phase AC voltage source is required to power a 3-phase induction motor with a capacity of 1.1 kW during the data recording procedure. During the current recording process, the 3-phase induction motor is subjected to mechanical and electrical loads via a coupling shaft connected to a 3-phase synchronous generator, which provides both resistive and inductive loads.

There are several signal processing tools available, including a computer running Labview, Diadem, and the NI Data gathering 9246 for current data gathering. Labview is connected with the data gathering equipment, so sample frequencies may be easily selected. The current measurement data will be analyzed using the FFT analysis technique. Following the FFT findings, the data will be analyzed in Matlab to calculate the amplitude of the frequency spectrum. The experimental system setup is shown in Figure 2.

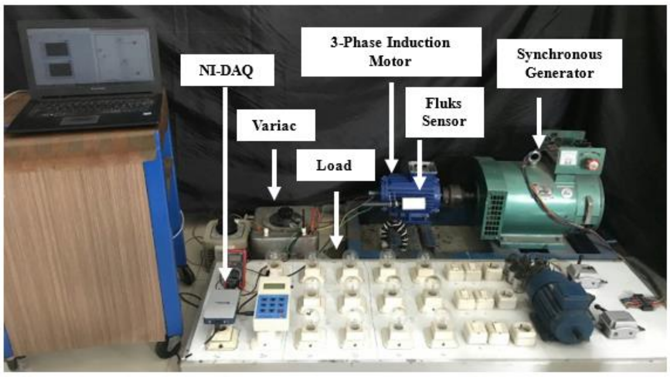


Figure 2. Configuration the unbalanced voltage detection system

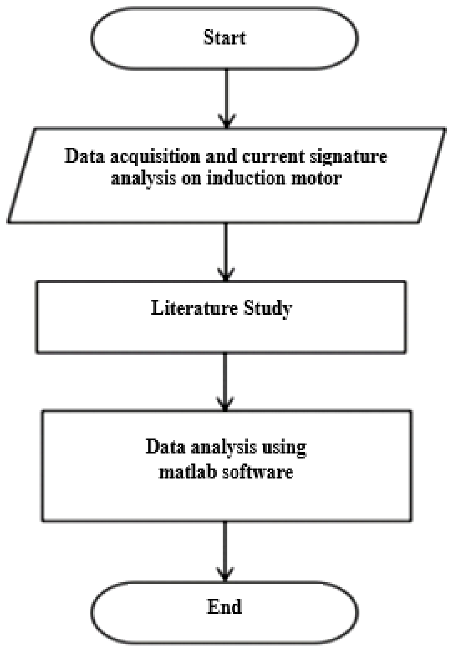


Figure 3. Flowchart of the experiment step

Figure 3 depicts the steps of this investigation. The first stage was to analyze the motor, which was the first phase of data collecting, employing current signature analysis devices on the three-phase induction motor. Following that, a literature study was carried out to obtain information on relevant theories, methodologies, and concepts for the topic. This information is useful for issue solving. The literature review required gathering material and references from textbooks, the internet, and other sources. The final and most important step was to analyze the data using Matlab software.

From the analysis using fast fourier transform, an induction motor diagnosis will be obtained which will be analyzed later. The research object used is an induction motor with a squirrel-cage rotor type which has a power rating of 1.1 kW. With the number of poles as many as 4, the speed at full load is 1.400 rpm and the operational frequency is 50 Hz.

IV. Result and Analysis

This testing procedure will be carried out in several stages, beginning with the collection of normal motor data with balanced and unbalanced voltages, followed by loading from 0 to 100%. Furthermore, it has several loading types, including no-load motors, generator loads, and incandescent lamp loads with 25 watts, 60 watts, and 100 watts. It's done to see how loading and unbalanced voltage affect motor efficiency. Table II shows the data testing method.

Table 1. Experiment Scheme

Load Case	**Variable Experiment**	
	Umbalaced Voltage Case	***Current Monitoring***
0%	Balance	Phase-R
25%	Over Voltage 5% (Phase R)	Phase-S
50%	Under Voltage 10% (Phase R)	
75%	Mix Voltage (OV 5% + UV 10%)	Phase-T
100%		

The specifications of the three-phase induction motor used in the lube oil bfpt pump motor are shown in Table 1. The motor power capacity is 1.1 kW, the working voltage is 380 V at a nominal current of 3.68 A. The nominal speed of the motor is 1.400 rpm, and the system frequency is 50 Hz.

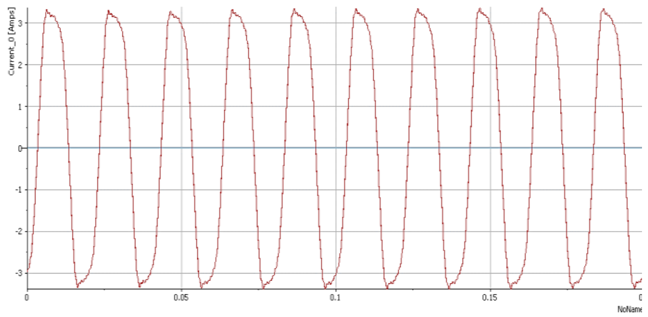
Table 2. Specification of Induction Motor

Parameter	**Units**
Output power	1.1 kW
Rotation speed	1.400 rpm
Voltage	220 V / 380 V
Current	6.36 A / 3.68 A
Frequency	50 Hz

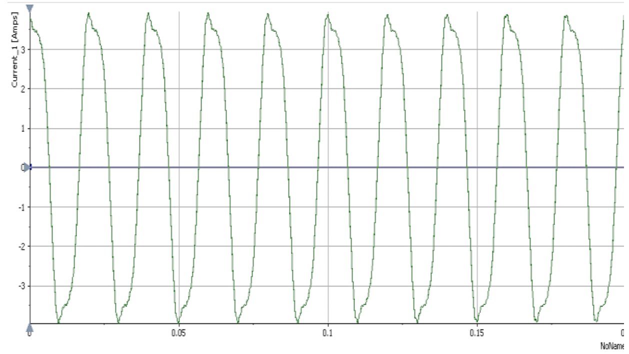
A. *Current Source Waveform with Unbalanced Voltage*

Data is collected by observing the current at the source on the R-phase, S-phase, and T-phase. In addition, observations were also made on the effect of unbalanced supply voltages on the performance of induction motors.

Figure 4 explains the results of current data on phase R, phase S, and phase T from the current in the stator. It can be seen from the three pictures that there is not much difference due to the disturbance caused by the voltage unbalanced.



(a)



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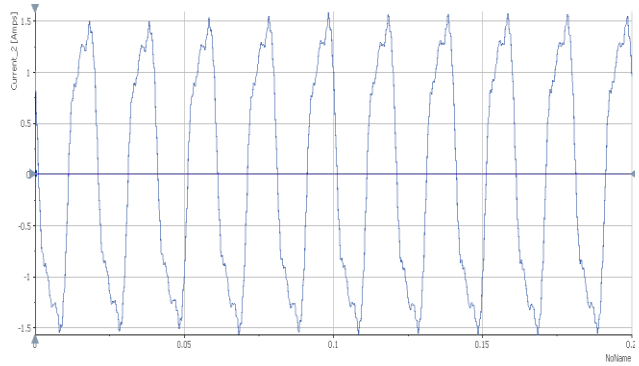
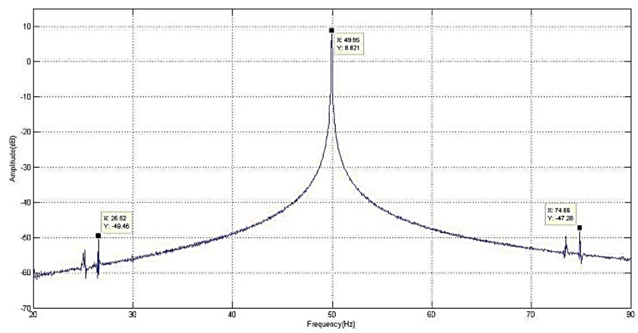


(c)

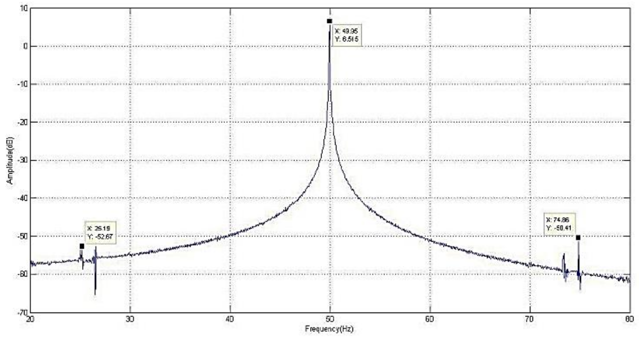
Figure 4. Current Waveform: a) R-Phase, b) S-Phase, and c) T-Phase



(a)

B. *FFT Analysis for Healthy Condition*

Data from healthy conditions have been analyzed using the FFT method. Later the spectrum of this healthy condition will be used as a reference for comparison with the unbalanced voltage condition. From Figure 5 it can be seen that in the low-band and side-band frequency sections, the amplitude values are still not very visible so that they can be used as a reference to distinguish them from unbalanced voltage.



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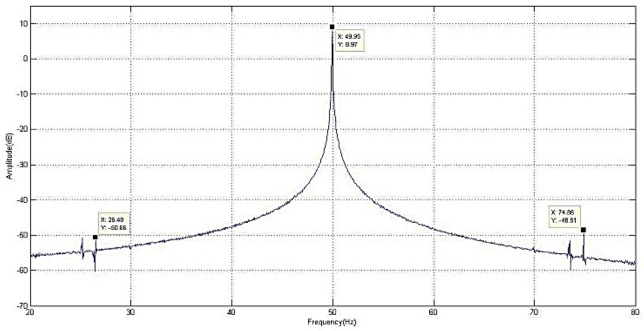
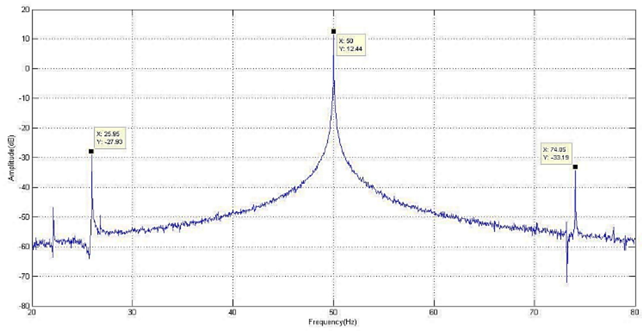


(c)

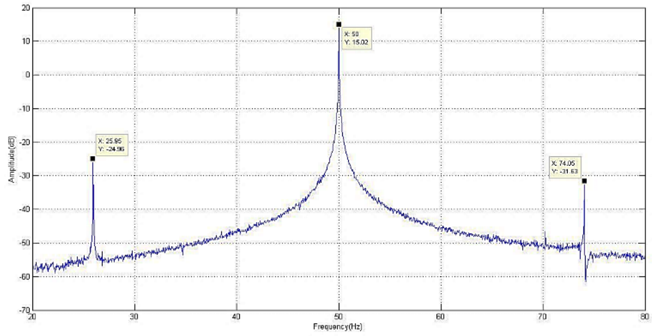
Figure 5. FFT analysis for healthy case: (a) Phase-R, (b) Phase-S, (c) Phase-T

C. FFT Analysis for Unbalanced Voltage Detection

From the case with an unbalanced voltage condition, the current spectrum is analyzed using a FFT so that different amplitude values are obtained from the low-band and high-band frequencies in the current spectrum in each phase.



(a)



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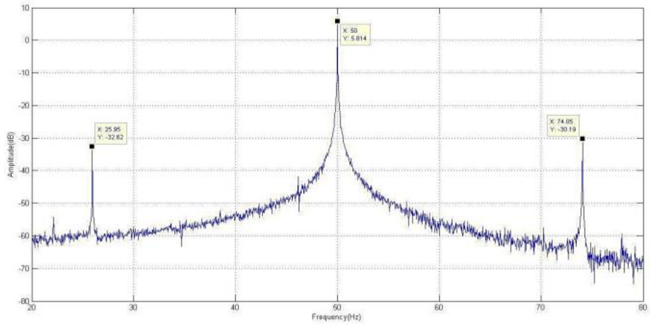

(c)

Figure 6. FFT Analysis for unbalanced : a) R-Phase, b) S-Phase, c) T-Phase

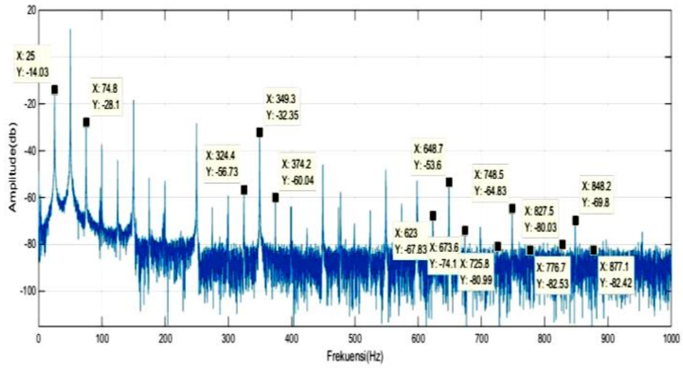

Figure 7. Observations with frequency magnification on the FFT spectrum

From the simulation results using Matlab, you can set the frequency limit you want to display, and you can plot the amplitude values of the harmonics to be analyzed. Of these several frequencies, not all of them are sensitive in detecting voltage unbalance disturbances. Further analysis is needed because every harmonic that appears can be influenced by many other things. Appearing harmonics are obtained from processing the frequency spectrum using the FFT which is measured by the data acquisition device.

Table 3. Comparison Result of Experiment

Condition	Amplitude of Low-Band Frequency			Amplitude of High-Band Frequency		
	Phase R	Phase S	Phase T	Phase R	Phase S	Phase T
Healthy	-49.46	-52.67	-50.66	-47.28	-50.41	-48.51
UV 10%	-28.32	-27.82	-38.47	-38.17	-32.02	-31.83
OV 5%	-27.93	-24.96	-32.62	-33.19	-31.63	-30.19
UV 5% + OV 5%	-30.31	-28.97	-37.05	-38.91	-33.52	-33.05

The results showed differences in the frequency spectrum pattern of the unbalanced voltage conditions. The unbalanced voltage with the test where the supply voltage on one of the phases is less than 5% or under voltage 5% is 209 V, and the other two phases are 220 V. After analysis using the fast fourier transform method, voltage imbalance failures can be detected. The value of the comparison of the magnitude of the amplitude at low-band and high-band frequencies under healthy conditions and under conditions of voltage imbalance is presented in table 3. This is evident in the large amplitude values on the low-band and high-band frequencies which have exceeded the amplitude values in healthy conditions. From the spectrum analysis using the fast fourier transform method, it is proven that the variation of the amplitude of the unbalanced voltage failure with the higher variation of the voltage level and the greater percentage of loading makes the spectrum irregular.

V. Conclusion

The results of the experiments that have been carried out, it can be concluded that the current signature analysis coupled with the fast fourier transform method can detect voltage imbalance failures in the supply of 3-phase induction motors through analysis of the amplitude values at each side-band frequency. In healthy conditions, the current spectrum resulting from processing using the fast fourier transform method only raises a small amplitude value in the low-band and high-band frequencies. On the other hand, when an unbalanced voltage is applied, the amplitude value at each frequency increases overall. The results were detected at frequencies of 25 Hz and 75 Hz with a high amplitude of -30 db, when compared with healthy conditions at this frequency there was no spike in amplitude values. So by using the MCSA method with the FFT approach analysis, it was successful in detecting voltage imbalance disturbances in 3 phase induction motors.

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