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A COST-EFFECTIVE COMPUTERIZED DATA ACQUISITION AND MOTOR CURRENT SIGNATURE ANALYSIS DEMONSTRATOR FOR INDUSTRY AND ACADEMIA

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ABSTRACT

This paper presents the development, results and trainee perception of a laboratory experiment used for diagnosing the occurrence of different faults in impeller-pump induction motors by means of the Motor Current Signature Analysis (MCSA) technique. This is a quintessential experiment, relatively inexpensive and easy to implement, that combines elements of computerized data acquisition, Discrete Fourier Transform analysis and fault identification of electric motors. Following this laboratory exercise, students and trainees are able to understand and apply MCSA to determine common faults of induction motors. The test stand, experimental setup, and test procedure are described with sufficient details in the paper for others to build one of their own.

INTRODUCTION

Detecting electrical or mechanical faults in induction motors is of prime importance for their safe and effective use. This paper discusses a combined laboratory experiment on Motor Current Signature Analysis (MCSA) of induction motors and LabVIEW™ programming that is inexpensive and easy to implement, yet effective and useful in the instruction of trainees from academia and industry.

Induction motors used in industry, in particular those that equip impeller pumps, can suffer from a variety of defects. These can be as follows [1] [2]:

- Stator faults, either open-circuits or short-circuits (i.e. between a phase and the ground, between two or more phases, or between different turns within the same phase);

- Rotor faults, including broken rotor bars and/or broken rotor end-rings;

- Bearing faults that result in static and/or dynamic air-gap irregularities;

- Bent shaft, a condition which over time can lead to rotor–stator rubbing and can damage both components, being particularly costly in large units.

Figure 1 shows a chart outlining the probability of occurrence of the most common induction motor defects [3].

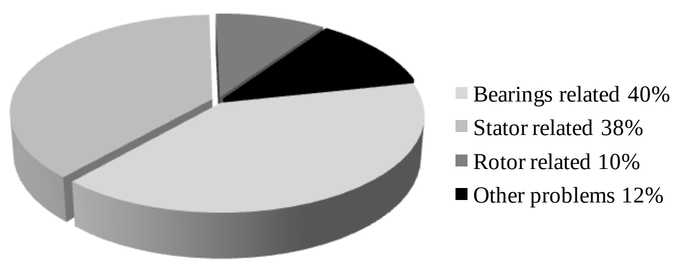


Figure 1.Main faults of induction motors.

There are several methods in use of evaluating the condition of induction motors i.e. monitoring of the speed fluctuation, vibration and acoustic emission, output torque, magnetic-field, temperature, current, as well as visual inspection, surge tests, partial-discharge measurement, gas analysis etc. [1-4].

Current monitoring has the advantage that it does not require expensive sensors for its implementation, and can be done without interfering with the operation of the motor. Usually the quantities of interest (voltage and current) can be easily extracted using readily available components of the protection system of the equipment such as current transformers coupled with protection relays [4]. If no current transformer is installed at the inspection site, MCSA can still be done noninvasively by connecting a clip-on current transformer around either one of the phases of a three-phase motor, or around the phase or the neutral cable of a single-phase motor.

Motor Current Signature Analysis (MCSA) is an electric machinery monitoring technology developed at the Oak Ridge National Laboratory [5], which detects current components caused by the unique rotating flux components produced by faults such as: broken rotor bars, air-gap eccentricity, shorted stator turns, bearing misalignment, bearing faults, load faults etc. MCSA processing of electric current data can be of frequency domain, time-frequency domain, wavelet transform or time series methods. The method implemented in the laboratory experiment discussed in this paper is of the Fast Fourier Transform (FFT) method, from the frequency domain category.

Compared to other technologies used for condition-based monitoring, MCSA requires moderate initial investments in hardware, but higher investment in software [6]. In this paper it will be shown that a MCSA demonstration and training stand can be easily built using commercial off-the-shelf components and NI data acquisition systems software for under 2500 US dollars. In most instances, part of these components may already be available at the user i.e. without the data acquisition system and LabVIEW™ software, the cost of building such a stand can be reduced by up to 90%. The input signal to the stand is the voltage measured on the shunt resistor mounted across a current transformer (Figure 2). This voltage is proportional to the current through the motor under consideration. The actual value of this current is not relevant, since the only entities of interest in MCSA are the frequencies, and the dB differences in the amplitudes of different frequency bands [6].

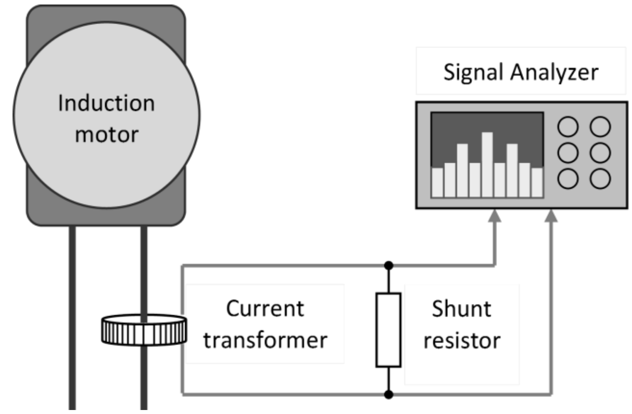


Figure 2.Schematic of the MCSA system.

EXPERIMENTAL SETUP

Part of their hands-on laboratory experience, trainees follow the instructions in a lab proceeding (see Appendix), and create a LabVIEW™ VI. Then they use this VI in conjunction with a MCSA test stand (see Figure 3), to determine the harmonic content of the currents dragged by the single phase motors of three induction-motors. Based on these measurements, they further determine if the respective motors have any defect, and then identify these defects.

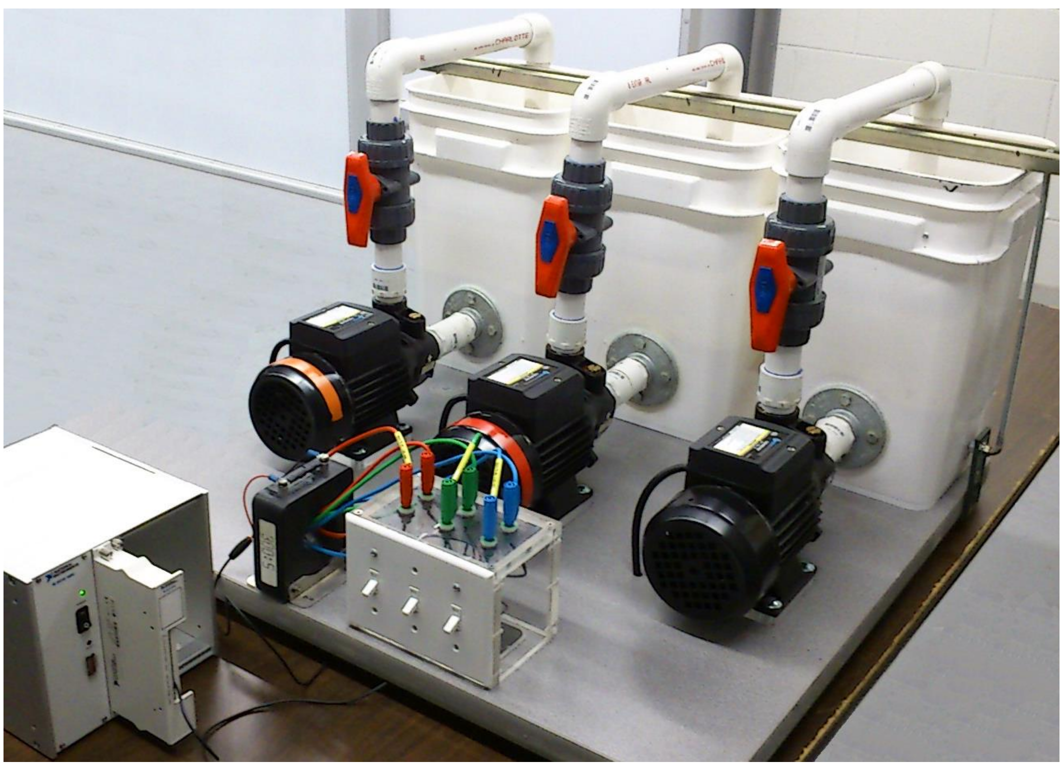
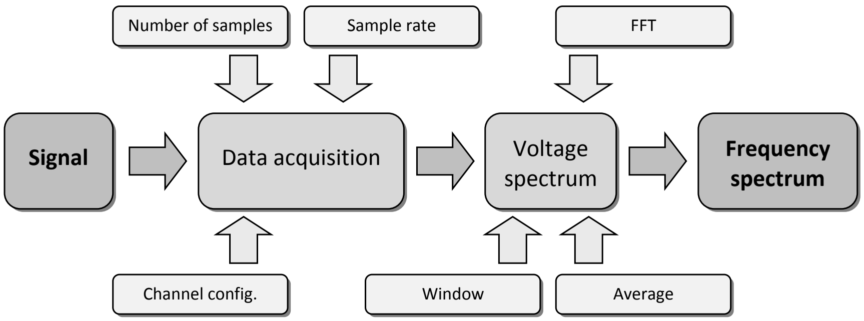
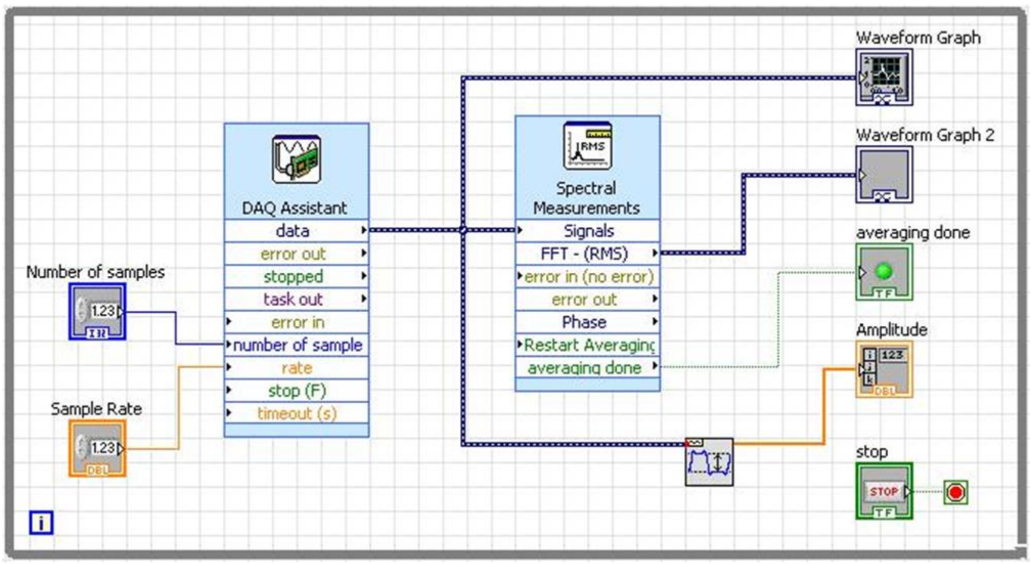


Figure 3. Single phase induction-motor pump stand, equipped with current transformer and data acquisition system.



(a)



(b)

Figure 4. Flow chart (a) and wiring diagram (b) of the of the LabVIEW™ VI used by the MCSA experiment.

The LabVIEW™ Virtual Instrument VI and its flow chart are shown in Figure 4. The VI serves to acquire the data from a specific channel of the DAQ board, with the number of samples and at a rate specified by the user. In order to achieve a good accuracy and to avoid spectral leakage, a common practice is to use a sampling frequency greater than five times the maximum detected frequency [7] [8]. In this experiment a rate of 10240 samples per second was used, and the number of samples was set to 40960. These allow five seconds per measurement at a frequency resolution of 0.2 Hz.

In order to avoid false-frequency detection caused by truncated signal segments, a *Hanning* window was applied to the input signal [7]. Then a Fast Fourier Transform analysis was performed. In order to minimize the noise amount and also to allow for more realistic readouts, five data sets collected successively were averaged. It has been observed that higher numbers of averaging sets taken over longer periods of time can result in frequency shifting of certain bands. These are associated with heavy motor loading, when the pump overheats and the trapped water changes physical properties.

The experiment discussed in this paper uses a stand that contains three single-phase centrifugal pumps, one current transformer (CT), a National Instruments data acquisition system and a computer running LabVIEW™ (see Figure 3). Table 1 shows a list of the components used in building this experiment, together with their approximate purchase price. To save cost, some of these components can be acquired used or refurbished, or may already be available to the user - the authors built their stand for less than 250 US dollars by already having the data acquisition system and a NI LabVIEW™ software license.

To avoid corrosion and seizing the pumps due to infrequent use, the pumps run in closed loop a mix of 25% engine antifreeze and 75% water. The load on these pumps can be adjusted by restricting the fluid outflow using one ball valve per pump (Figure 3). Of these three pumps, one is free of defects, one has an electrical fault, and one has an eccentric rotor. The electrical fault consists of two broken rotor bars (out of a total of 18 bars), induced by drilling radially through these two bars. The air-gap eccentricity was obtained by inducing a clearance between the fan-end of the shaft and the inner race of its ball bearing. In order to exacerbate this fault, an unbalance was added by attaching a small bolt to one of the blades of the fan.

Table 1. MCSA lab equipment component list

Item	**Manufacturer**	**Model / Version**	**Approximate cost US dollars**
Data Acquisition System	National Instruments	Chassis: SCXI-1000	$325
		Board: SCXI-1102	$1150
		Extension: SCXI-1303	$240
		PC Board: PCI-MIO-16E4	$320
Current Transformer	Square D Co.	64R-301	$85
Clear-water pumps	Pacific Hydrostar	120V/60Hz/5 A	3 × $48
Ball Valves	TrueUnion	FNW340NE	3 × $26
Miscellaneous components			$133
		TOTAL:	**$2500**

The current transformer used in this experiment has a ratio of 300 to 5. Any current transformer that allows a primary current of at least 10 A should work equally well. For the pump nominal current of 5 A, the current in the secondary winding of the transformer is 0.083 A, thus producing a voltage of about 2.08 V across a 25 Ω shunt resistor. The power dissipated in the shunt resistor is about 0.17 W, so a resistor with a rated power of 0.5 W should suffice. To increase the voltage across the shunt resistor and into the data acquisition board, more than one connecting-cable loop can be run through the current transformer (Figure 3).

Care must be taken so that the core of the transformer does not enter saturation, the voltage across the shunt resistor does not become dangerously high, and that the shunt resistor can safely dissipate its power. Students or trainees should also be instructed not to allow the motors run more than necessary while testing on medium and heavy loads, since this could lead to pump overheating which are usually associated with frequency sideband deviations.

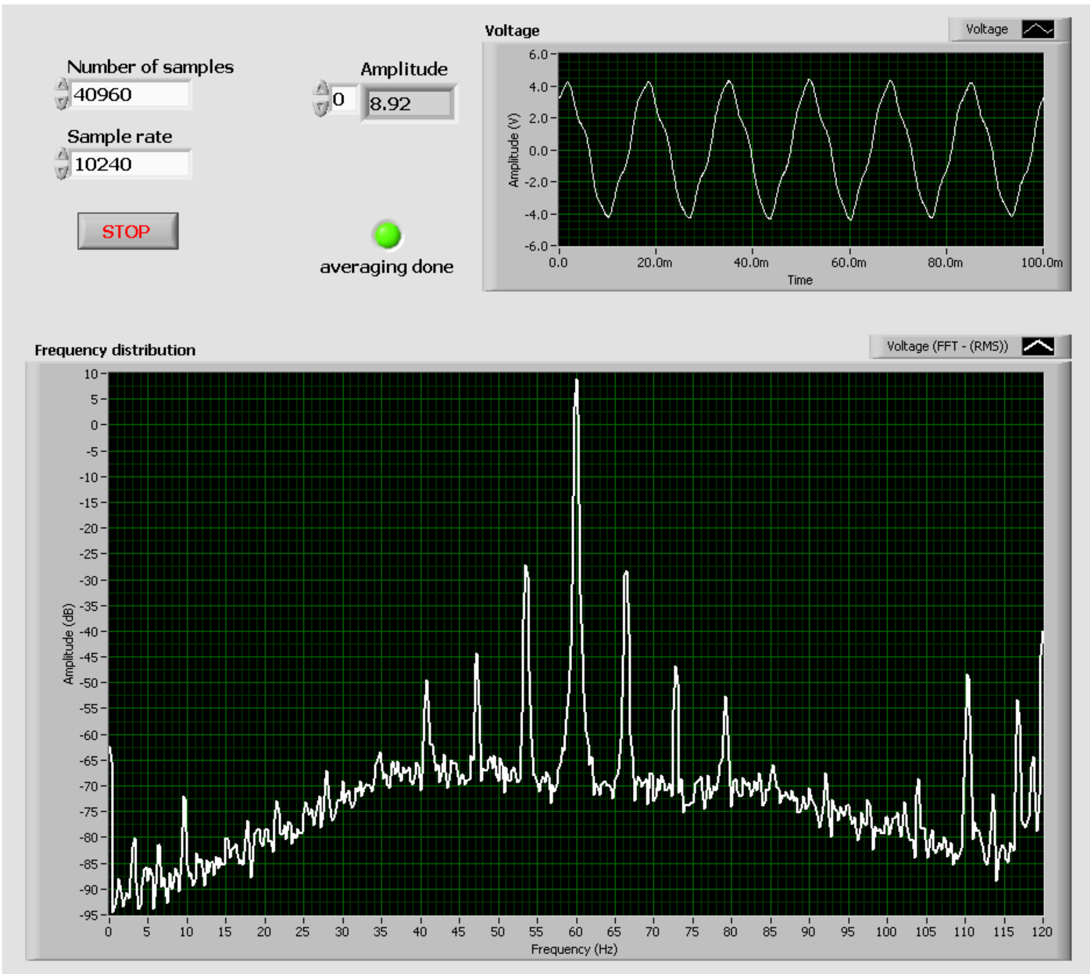


Figure 5. Time and frequency domain plots corresponding to the lightly loaded pump with broken rotor bar motor.

SIGNAL ANALYSIS

The wiring diagram of the VI that must be generated part of this laboratory exercise is shown in Figure 4-b. A screenshot of the corresponding front panel is provided in Figure 5.

Three measurements for each of the pumps are taken at light load, medium load and maximum load. The trainees save to the computer's hard drive the screenshots from the VI, the detailed frequency spectrum data and the sampled voltage data. They are also assigned to plot, using Office Excel™, the frequency distribution of the data saved from LabVIEW™. Then they perform using Excel a Fast Fourier Transform analysis of the sampled voltage data - see Appendix and [9].

Having all the data stored, the supply frequency and the side-bands can be identified using the following equation [6]:

$$f_{sb} = f_1(1 \pm 2s)[Hz] \qquad (1)$$

where f_{sb} is side-band frequency, f_1 is the supply frequency and s is the induction-motor slip.

According to [6], differences of 50 dB or more between the supply frequency amplitude and the amplitude of the side-bands, suggest a healthy induction motor. If the sideband frequencies do not have the same amplitude, the sideband with the highest amplitude (worst case) must be taken into consideration. Such differences are evident on the front panel of the VI with the pump running (see Figure 5). The frequency amplitudes for all the three pumps under full load are shown in Figure 6, case in which the pump with the faulty rotor can be quickly and unequivocally identified.

After deciding on the health of the motor, the trainees can also check for air-gap eccentricities in each motor according to the equation:

$$f_{ec} = f_1\left[(R \pm n_d)\left(\frac{1-s}{p}\right) \pm n_{ws}\right][Hz] \qquad (2)$$

where

f_{ec} = frequency components function of air-gap eccentricity in Hz;

f_1 = supply frequency in Hz;

R = number of rotor slots;

n_d = -1,0,1;

n_{ws} = 1, 3, 5…;

s = slip (calculated from the positions of the sidebands);

p = number of pole pairs.

For the experiment described, the supply frequency is 60 Hz, there are 18 rotor slots and 2 pole pairs. Equation (2) indicates where local maxima occur in the case of static (n_d =0) or dynamic ($n_d = \pm 1$) eccentricities [10] [11]. The user can search for these maxima directly on the corresponding frequency plots, or by inspecting the data columns within Excel. It is important to mention that static and dynamic rotor eccentricity effects are usually difficult to separate, and that large static eccentricities may induce dynamic eccentricities as well.

The trainees performing the experiment then summarize their finding in a table that contains (a) the side-band frequencies, (b) the amount of slip, (c) the dB difference between the side-band frequencies and the power supply frequency. In a written report they comment on their findings and on the condition of each motor.

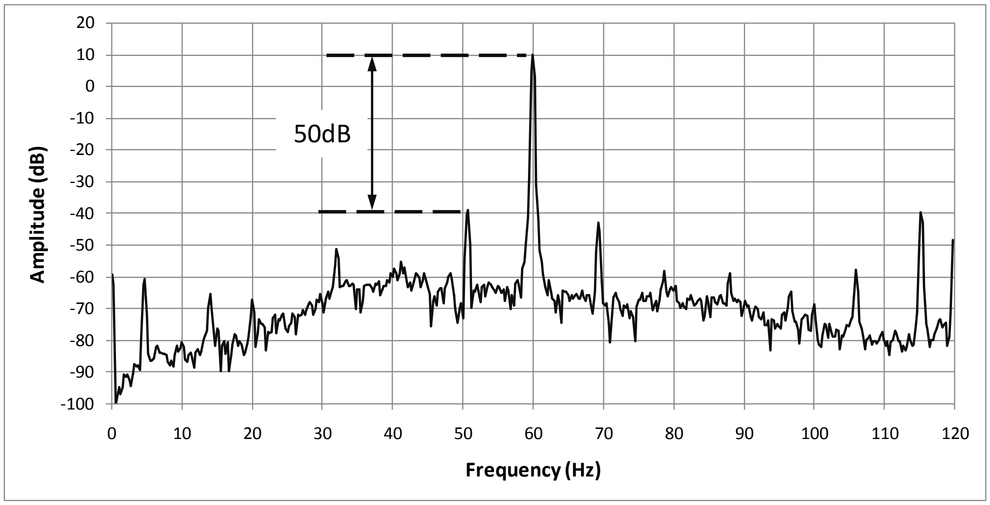
TRAINEE ASSESSMENT

Hands-on training is an integral part of undergraduate engineering education [12], as well as of workforce development. After the completion the experiment, the students taking an Instrumentation course at Texas A&M University Corpus Christi were given a six-question survey to evaluate their perception of the experiment. In addition they were asked to provide comments and suggestions for improvements of the MCSA laboratory exercise. The questions together with the averaged responses gathered over two academic semesters are listed in Table 2. The response distributions were organized in histograms for each question, as shown in Figure 7.

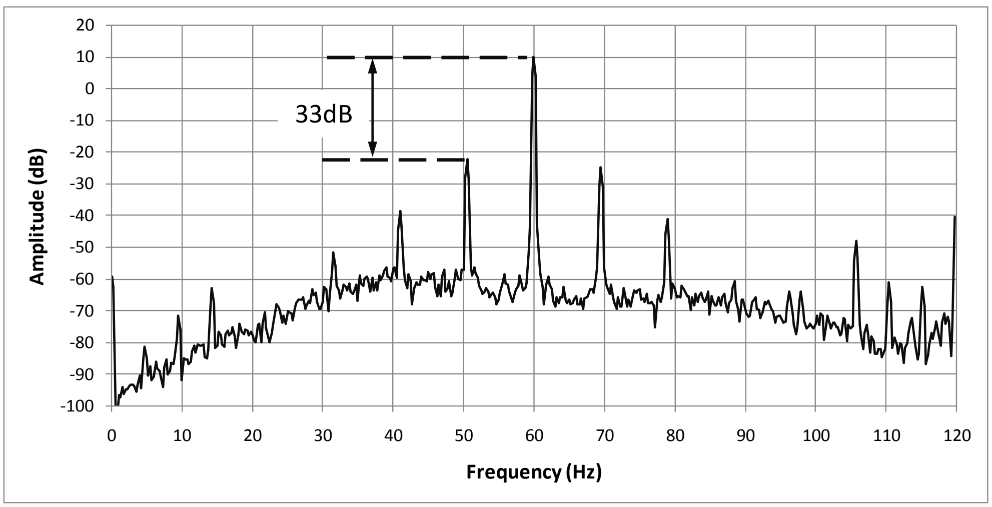
Table 2. Summary of student perception of the MCSA lab.

Question	Average Response
1. The laboratory did a good job of familiarizing me with computerized data acquisition and LabVIEW programming.	4.89 of 6
2. The experiment provided a good introduction to single-phase induction motor construction and potential defects.	5.37 of 6
3. The experiment did a good job of familiarizing me with MCSA-based condition monitoring of electric motors.	5.16 of 6
4. Following this lab exercise I am interested in learning more about condition monitoring of electric machines.	4.68 of 6
5. Following this lab exercise I am interested in learning more about condition monitoring in general.	4.74 of 6
6. This lab experiment should be offered in the future.	5.32 of 6

To the questions pertaining to the success of this laboratory (i.e. questions 1, 2 and 3 in Table 2), most responses were towards the upper scale, suggesting that the objectives of the lab have been accomplished. Overall, the students found the lab to be useful, interesting and somewhat challenging.



(a)



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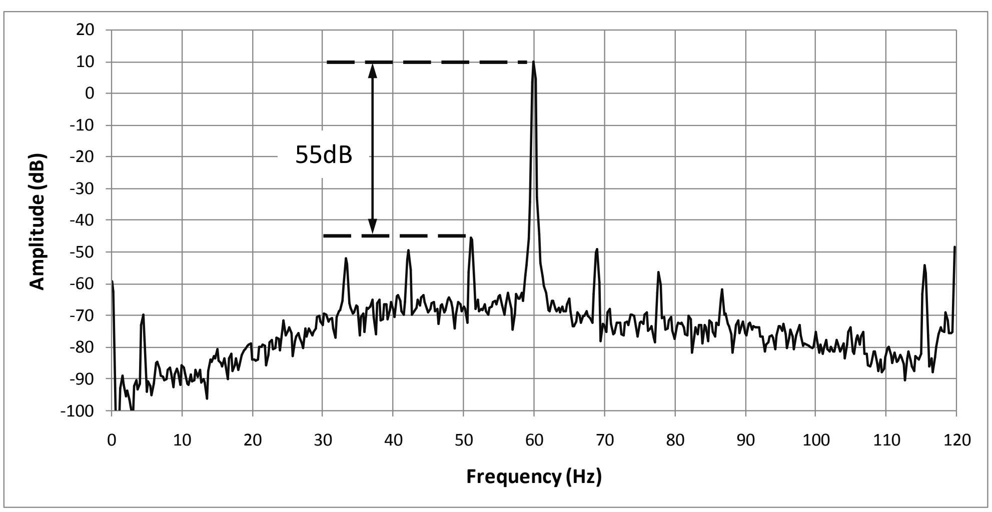

(c)

Figure 6. Frequency content under full load for the healthy pump (a), the pump with broken rotor bars (b) and the pump with air-gap eccentricity (c).

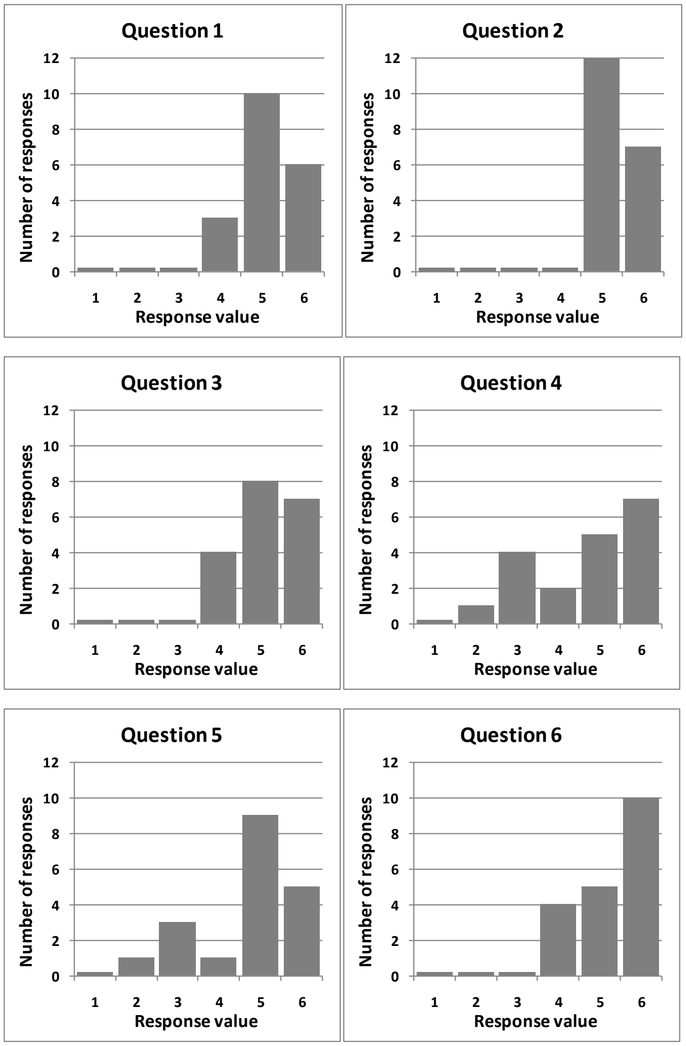

Figure 7. Histogram results for the survey, where 1 = strongly disagree and 6 = strongly agree.

CONCLUSIONS

A laboratory experiment developed by the authors have been presented in the paper. The aim of the experiment is to familiarizing trainees from academia and industry with MCSA condition monitoring of induction motors, and with computerized data acquisition using LabVIEW™ software. The experiment stand itself can be very inexpensively built, provided that a data acquisition system already exists. The LabVIEW™ programming part can be omitted, placing emphasis on identifying the faults of the electric motor. As the survey results presented show, engineering students performing the experiment as described, agreed that it provided a useful insight to MCSA condition monitoring and induction motor inner workings, and to LabVIEW programming.

ACKNOWLEDGEMENTS

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APPENDIX

LABORATORY PROCEDURE

Electrical

1. Make sure that the shunt resistor is connected across the current transformer;

2. Verify the connections of the cables for each pump circuit and make sure each cable passes twice through the current transformer. It is not necessary to center the cables inside the current transformer window;

3. Connect the signal cable from the current transformer to a voltage input channel on the data acquisition board (e.g. CH18);

4. Set all three valves to the *maximum open* position;

5. Make sure that the data acquisition board is *on* and connected to the PC. If not, connect and power it first, and only then turn the computer *on*.

LabVIEW programming:

1. Start LabVIEW and open a blank VI;

2. In the Block Diagram pull up the Functions Palette (View – Functions Palette). Do the same for the Control Palette in the Front Panel;

3. From the Functions Window in the Block Diagram, select Express / DAQ Assist and place the block inside your diagram;

4. The configuration window of the DAQ Assistant will appear; select Acquire Signals – Analog Input – Voltage – SC1Mod1 (SCXI-1102C) – Your Input Channel (e.g. 18). Then click Finish. In the next window select Input Range (max 10 V, min -10 V), the number of Samples to Read (i.e. 40960), and Rate (i.e. 10240), then click OK.

5. Right-mouse click on the Number of Samples pin of the DAQ block and select Create – Control. Do the same for the Rate pin. These controls will be used if you want to change the acquisition parameters from the Front Panel. Switch to the Front Panel to see these changes.

6. From the Functions Window in the Block Diagram, select Express / Signal Analysis / Spectral and place the block inside your diagram; in the window that appears, select:

   Measurement: Magnitude (RMS);

   Result: dB;

   Window: Hanning;

   Averaging: Yes;

   Mode: RMS;

   Weighting: Linear;

   Number of Averages: 5;

   Produce Spectrum: Every Iteration;

and then click OK.

7. Wire the Signal pin of the Spectral Measurement block to the Data pin of the DAQ block.

8. From the Controls Palette in the Front Panel, select Express / Graph Indicator / Graph and drag the block in the Front Panel. Wire this newly created Waveform Graph to the Data pin of the DAQ block.

9. Right-mouse click on the FFT-(RMS) pin of the Spectral Measurement block and click Create – Graph Indicator.

10. Right click on the Averaging Done pin of the Spectral Measurement block and click Create –Indicator.

11. From the Functions Window in the Block Diagram, select Signal Processing / Waveform Measurements / Ampl & Level and place the block inside your diagram; wire the Signals In pin to the Data pin of the DAQ block, and create an indicator for the Amplitude pin.

12. From the Functions Window in the Block Diagram, select Express / Exec Control / While Loop and drag the loop around all the blocks in your diagram. The Block Diagram and the Front Panel should look similar to the ones in Figures 4-b and 5.

13. Right Click / Properties on the graphs in the Front Panel to change the axis ranges and names.

Measurements

1. Deactivate the auto scaling feature on the X axis of the graph (right click / uncheck Auto Scale X) and set the frequency range on the FFT graph to 0 – 120 Hz.

2. Set the valve for the first pump to the *open* position.

3. Turn the first pump (healthy motor) *on* and then start the data acquisition by clicking Run on the Front Panel.

4. Right click on the voltage waveform graph and select Export / Export Data to Clipboard, and then open the data in Microsoft Excel for future reference.

5. After averaging is complete (green indicator), right-mouse click on the frequency graph and select Export / Export Data to Clipboard, and likewise insert the data in Microsoft Excel for future reference. Turn off the pump and stop the data acquisition. On the displayed frequency chart, identify with the help of Equation 1 the supply frequency and the side-bands.

6. Set the ball valve to *half-closed* position and repeat steps 3 to 5.

7. Set the valve to *completely closed* position and repeat steps 3 to 5. Do not allow the pump run more than 30 seconds to avoid overheating.

8. Repeat steps 2-7 for the second pump.

9. Set the frequency range on the FFT graph to 0 – 2000 Hz.

10. Repeat steps 2-7 for the third pump. Estimate using Equation 2 at what frequencies should the local amplitude maxima occur.

11. Use Excel to find the maxima in the data. Calculate, represent and store the FFT spectrum in Excel (see instructions in Appendix). Organize your results in a table showing the

pump number, the load, the side-bands frequencies, the slip, the difference between the central frequency and the slip frequencies in dB, and conclude whether the pump is faulty of not.

FFT with Excel

1. Open Excel and create a new spreadsheet file. Add the title "Time" to the A column, followed by the titles "Data," "FFT Frequency," "FFT Complex" and "FFT Magnitude" to columns B through E respectively.

2. Input the data from your voltage waveform measurements into the Data column. Make a note of the number of data points and the sampling rate used.

3. Write the time at which each data point was acquired in the Time column. Determine this by dividing the total time by the number of data points.

4. Open the "Data" tab, and then select "Data Analysis". If the tool is not there, go to Excel Options > Add Ins > Manage, select the tool and press OK. Select the "Fourier Analysis" option and press the OK button. Set the input range as the information in the Data column and the output as the FFT Complex column. Make sure that the number of input values is a power of 2 (for example 1024).

5. Type the equation "=2/N*IMABS(D2)" (N is the number of samples) into the first cell of the FTT Magnitude column. Drag the equation downward to fill every cell of the column. This equation creates real numbers, instead of complex numbers, in the previous column.

6. The first value in the FTT Frequency column is always 0. The cell C3 will be 1xS/N, where “S” is the sampling rate and “N” is the number of samples. After you calculate cell C3, select it and go to Home > Fill > Series; select “Series in columns”, “Linear”, and enter S/N for “Step value” and S for “Stop Value”.

7. Create a graph, using the FTT Magnitude column for the y-axis and the FTT Frequency column for the x-axis. The graph displays the dominant frequencies as peaks. You can select a shorter frequency range to better identify certain peaks. The maximum range should be up to the middle point of the measurements, otherwise the sequence will start to repeat itself.