Investigation of Relationship between Mechanical Vibration and Energy Consumption of an Induction Motor

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Abstract

Vibration diagnosis of induction motor operation has many cases such as imbalance, misalignment, bearing defect, and so on. These causes have been continuously studied and researched to reduce mechanical vibration of an induction motor. The mechanical vibration is one of the reasons for decreasing motor efficiency, increasing energy consumption and also maintenance time. The purpose of this research is to find a relationship between mechanical vibration and energy consumption of an induction motor. This research simulates the motor operating situation and concentrates on mechanical vibration that may affect energy consumption at various motor speeds. Then there is the creation of an energy consumption regression equation by analyzing variances (ANOVA). The result shows the energy equation as 85% coefficient of determination. Therefore this approach can estimate that if vibration amplitude is higher, the energy consumption will also continually increase as 97% accuracy compared with experiment data.

Keywords : Mechanical vibration, Energy consumption, Induction motor, Coefficient of determination

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1. Introduction

The causes of mechanical vibration occurring in induction motor operation include imbalance, misalignment, mechanical looseness, belt defect, bearing defect, and so forth. These causes have been continuously improved and efforts made to try to avoid them so as to reduce breakdown of the motor operation and time required for maintenance. Mechanical vibration is one of the reasons for decreasing motor efficiency and increasing energy consumption.

Most previous research has emphasized mechanical vibration to be a sign of the unusual working of the induction motor such as by studying unusual electromagnetic coils by using vibration amplitude to be the indicator. The result demonstrated that if the vibration amplitude is high then the power load motor will also be high because of the unusual electromagnetic coils of the motor [1]. And there was investigation of imbalance and looseness of shaft angular alignment by using vibration analysis and acoustic emission techniques to detect the system. The results show that acoustic emission techniques offer more capability and reliability than vibration analysis for investigating mechanical looseness diagnoses [2-3]. Moreover, there was some research study about factors that might affect operation of the system and motor efficiency such as stator core, electromagnetics, a supply voltage imbalance, the teeth of the stator, winding, outer casing, slot, and end-shields. The results demonstrated that all of the factors affected decreased motor efficiency and increased energy consumption [4-5] and another research used vibration signal to investigate multi-class fault diagnosis such as bowed rotor, broken rotor bar, bearing fault, healthy motor, rotor unbalance, stator fault, and voltage unbalance.The results demonstrated that the vibration signal can diagnose all of the factors [6]. In addition vibration signature analysis was used to investigate the relationship of current and power signature analyses. The result demonstrated failure of gear box that affected current consumption [7]. And there were another research that shows of the relationship of vibration signal and motor efficiency by a non-intrusive method as the average error of perdition equation was 3.5% compared with all three test motors [8]. And in another research, there was investigation of bearing problems that affected energy consumption by using vibration analysis signals for comparison [9]. As previous researches have been not found that these researches created the mechanical vibration model. Therefore the scope of this research studies vibration signature analysis that varies with shaft speeds to monitor motor energy consumption and creates the energy consumption regression equation model by analyzing variance (ANOVA) to use this model as an investigated guideline for maintenance operating.

2. Materials and Method

The experimental setup monitors vibration amplitudes and energy consumption. An unbalanced mass vibration was applied in experiments as shown in Figure 1. The unbalanced mass vibration system consists of unbalanced mass (m), mass primary in the system (M), distance of the unbalanced mass from the rotating axis (e), angular velocity (ω), spring stiffness (k), and damping coefficient of the damper (b). This system used unbalanced dish load impacting the induction motor operation to create vibration analysis as shown in Figure 2. Chermthongi, 2006 proposed the motion equation had two steps as transient response and steady-state response, as in equation (1).

$$m\ddot{x} + b\dot{x} + kx = f(t) \qquad (1)$$

$$f(t) = me\omega^2 \sin \omega t \qquad (2)$$

Equation (2) is the motion equation of vibration analysis by using the unbalanced mass to be a harmonically varying force.

Fig. 1 Experiment and getting results of data

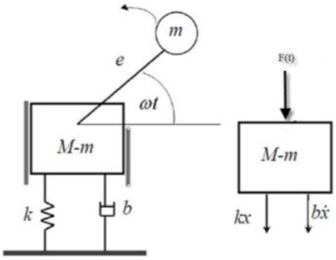

Fig. 2 The unbalanced mass vibration system

Equation (3) is amplitude vibration that can be presented under impacted force.

$$X = me\omega^2 / [(k - M\omega^2)^2 + b^2\omega^2]^{1/2} \qquad (3)$$

Figure 3, shows the frequency response of system in the unbalanced mass vibration system [10]. After setting the vibration generator, the experiment collected data about vibration displacements, motor speeds, and electric energy consumption of the motor.

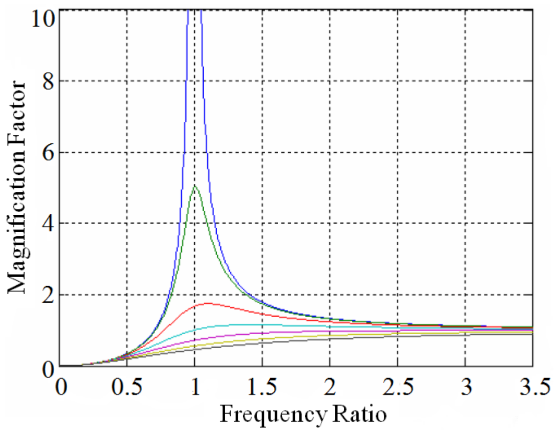

Fig. 3 Frequency response of the system with unbalanced mass

The measurement ranges were 10 Hz to 5,000 Hz, displacement range: 0.1 to 1.999 mm (p-p), velocity range: 0.1 to 199.9 mm/s (RMS), and acceleration range: 0.1 to 199.9 m/s^2 (PEAK). Power meter that was used in our preliminary experiments was C.A 8331 CHAUVIN ARNOUX. The application was 1,000 V in CAT III and 600 V in CAT IV, Harmonics from 0 to 50th order, and active power: 10 mW to 10 MW.

The experimental setup was used to simultaneously estimate the energy consumption with motor speeds and vibration amplitudes to find the related equation of energy consumption and factors as shown in Figure 3.

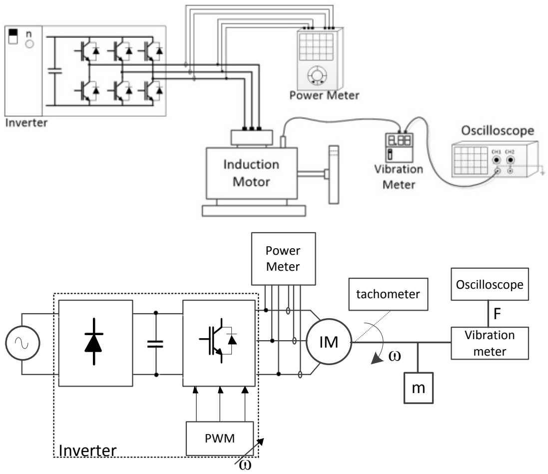

Fig. 4 Experimental device setup

The experimental setup that was used in this research is shown in Figures 4 to 7. The induction motor used was a HASCON HA802-4, 1HP, 380 V, 4 pole, and 50 Hz and assembled with unbalanced mass.

The measurement device that was used in this experiment was Agilent InfiniiVision DSO-X 2012A Oscilloscope. The specification was an 8.5-inch WVGA display, fastest update rate of 50,000 waveforms per second, and memory of 100 kpts standard up to 1 Mpts optional. The vibration signature analysis used DIGIVIBRO 1332A.

Fig. 5 The motor with unbalanced mass assembly

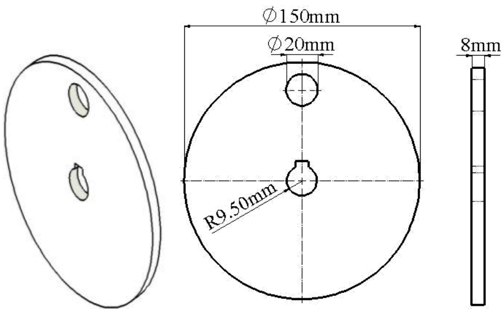

Fig. 6 An unbalanced dish

The designed investigation plans were conducted for experiments with the following conditions:

- Set motor speed by ranging 350 to 1,600 rpm.
- Use accurate measuring instruments.
- Well-defined and clear specifications.
- All the results will be employed into analyzing of variance (ANOVA) stage for seeking influent

parameters according to research's Oscar et al [11]. The main and interaction effects will be provided from this statistical methodology.

- All experiment results are verified with the true values appraised by the competent analysis under regression model analysis.

3. Results and Discussion

The experiment tests recorded vibration amplitudes (VA), shaft velocities (*SV*), and power consumption (*P*).Then analyzing variances (ANOVA) was selected to consider the significance of the model terms for the power consumption as in Figure 7. The term "DF" is degree of freedom. "Seq SS" is the sum of squares for each term. It is used to validate of the data. "df" refers to degrees of freedom used to contribute to the error prediction. "Adj SS" is adjusted sum of squares that is used to be a sign after removing insignificant terms from the model. "Adj Ms" is adjusted mean squared for a term. Then the model is processed using the backward term elimination, which means some of the terms that are not significant are cut .Finally, Figure 7 show that "P-value" is less than 0.05 and the values of "R-Sq (prediction)" were 86.67%. Therefore, this result found that Shaft velocity (SV), Vibration amplitude (VA), and Shaft velocity (SV) * Vibration amplitude (VA) are significant.

After gathering experiment data, analysis of variance (ANOVA) was used to determine the relationship between input and output variables of the system. For modeling, the energy mathematical function by polynomial model was used. The model polynomial in this research used two factor interaction models as in equation (4) [12]

$$E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 \quad (4)$$

The interpretation of parameter β_0 is $\beta_0 = E(y)$ when $x = 0$ and it can included in the model provided the range of data includes $x = 0$.If $x = 0$ is not included, than β_0 has no interpretation. β_1 and β_2 are the coefficient of the linear effect parameters. β_{12} is the coefficient of the interaction effect parameter.

Then the polynomial model was modified and there is use of an analysis of variance (ANOVA) as confidence intervals 95%. Terms with confidence intervals of higher than 95% (P-Value less than 0.05) were selected. These terms with their corresponding P-values are reported in Table 1 by all parameters created in Minitab software. The energy consumption model will be used to be sign of electric power that relates with mechanical fault of induction motor operations.

The experiment results are indicated in Figures 8 and 9. They illustrate the vibration displacement, motor speed, and energy consumption values. As in Figures 8, it can be found that if the vibration amplitude continuously increases, the power consumption will also be progressive. Likewise,

Figure 9 that show the correlation between power consumption and motor speed has a same tendency as Figure 8. Moreover, vibration amplitude range at 0.15 mm to 0.241 mm illustrates in Figure 8 that they have variant power consumptions because at high vibration mechanical fault, electrical unbalance will happen affected to variant power consumption recorder.

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Estimated Effects and Coefficients for Power consumption

Term                                Effect    Coef  SE Coef      T      P
Constant                                    31.212   0.9903  31.52  0.000
Shaft Velocity                      35.064  17.532   1.9857   8.83  0.000
Vibration Amplitude                 -8.730  -4.365   1.9852  -2.20  0.038
Shaft Velocity*Vibration Amplitude -12.574  -6.287   2.5197  -2.50  0.020

S = 3.80712   R-Sq = 86.67%   R-Sq(adj) = 85.00%

Analysis of Variance for Power consumption (coded units)

Source              DF   Seq SS   Adj SS   Adj MS      F      P
Main Effects         2  2170.76  1829.62   914.81  63.12  0.000
2-Way Interactions   1    90.24    90.24    90.24   6.23  0.020
Residual Error      24   347.86   347.86    14.49
Total               27  2608.86

Estimated Coefficients for Power consumption using data in uncoded units

Term                                     Coef
Constant                              4.85859
Shaft Velocity                      0.0342539
Vibration Amplitude                   31.2465
Shaft Velocity*Vibration Amplitude -0.0754751
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Fig. 7 Estimated Effects and Coefficients for Power consumption via Minitab software

Table 1 Value results for power consumption model

Predictor	P-value
Constant	0.000
Motor Speed	0.000
Vibration Amplitude	0.038
Motor Speed* Vibration Amplitude	0.020

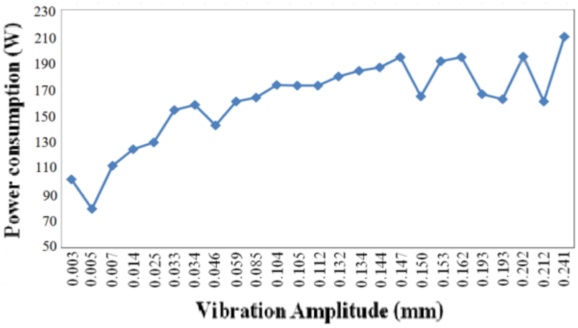

Fig. 8 Correlation between power consumption and vibration amplitude

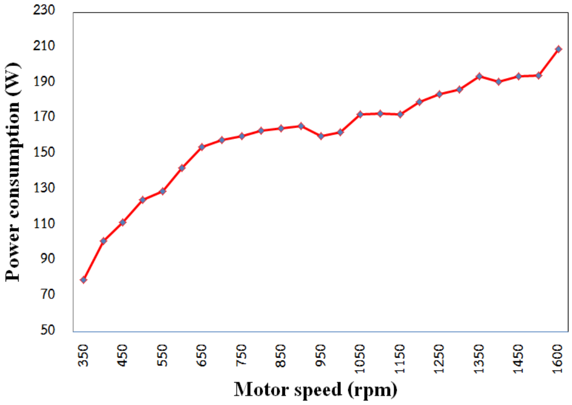

Fig. 9 Correlation between power consumption and motor speed

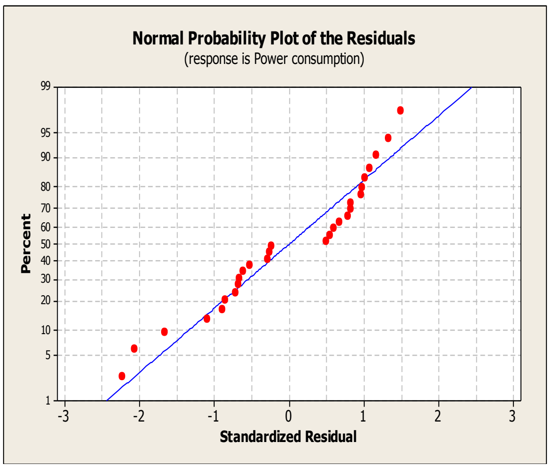

Fig. 10 Normal test for power consumption results

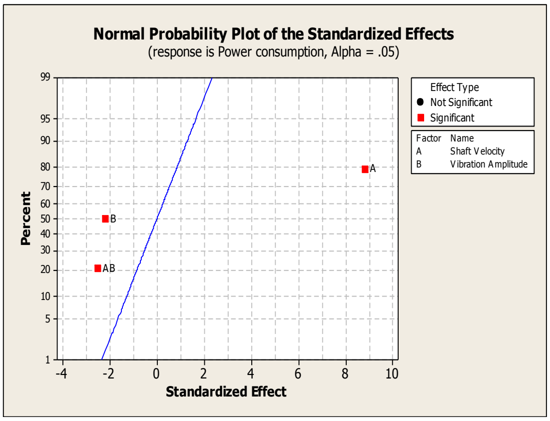

Fig. 11 Normal Probability of variable factors

Furthermore, correlation of motor speed and vibration amplitude factors that affected energy consumption can check the validity of the models normal probability plot of residuals as shown in Figure 10. And in Figure 11 indicated that shaft velocity (*A*), vibration amplitude (*B*), and an interaction of shaft velocity with vibration amplitude were significant. Based on Figures 10 and 11, the model is normally distributed. Low dispersion of the points from the reference line indicates high quality of the models. The selected model is shown in equation (5). This model was used for predicting energy consumption to investigate abnormal motor operation via shaft velocity and vibration signal factors.

The polynomial model is:

- Output parameter: power consumption (*P*)
- Input parameters are: Shaft velocity (*SV*) and Vibration amplitude (*VA*)

$$P = 4.85859+0.0342539*(SV) + 31.2465*(VA) - 0.0754751*(SV*VA) \quad (5)$$

As per Figure 12, it can illustrate experimental energy consumption compared with estimated energy consumption that was gained from the regression model. There was a gradually increasing trend of energy consumption along with increased vibration amplitudes.The equation model can ensure that there was only 3% error from actual energy consumption of the motor operation that calculated from the percentage of predicted energy and actual energy differences.As these reasons,the results indicate it can be used to highly recommend improving induction motor efficiency and avoiding mechanical vibration of motor operation because they are an correlation between mechanical vibration and power consumption of induction motor.

According to [1, 9-10] mentioned about the relationship between vibration signal, motor efficiency and energy consumption. The results were found that the mechanical vibration signal can represent the mechanical faults that had the relationship with energy consumption, and efficiency of motor operation and used vibration diagnose to be the sign for monitoring operation efficiency. Therefore, this research also present the vibration signal and energy consumption of induction motor and generating the regression model in order to predict power consumption at various vibration amplitudes and shaft velocities of induction motor. This model will provide the operation guideline to investigate all unusual case in the motor operation.

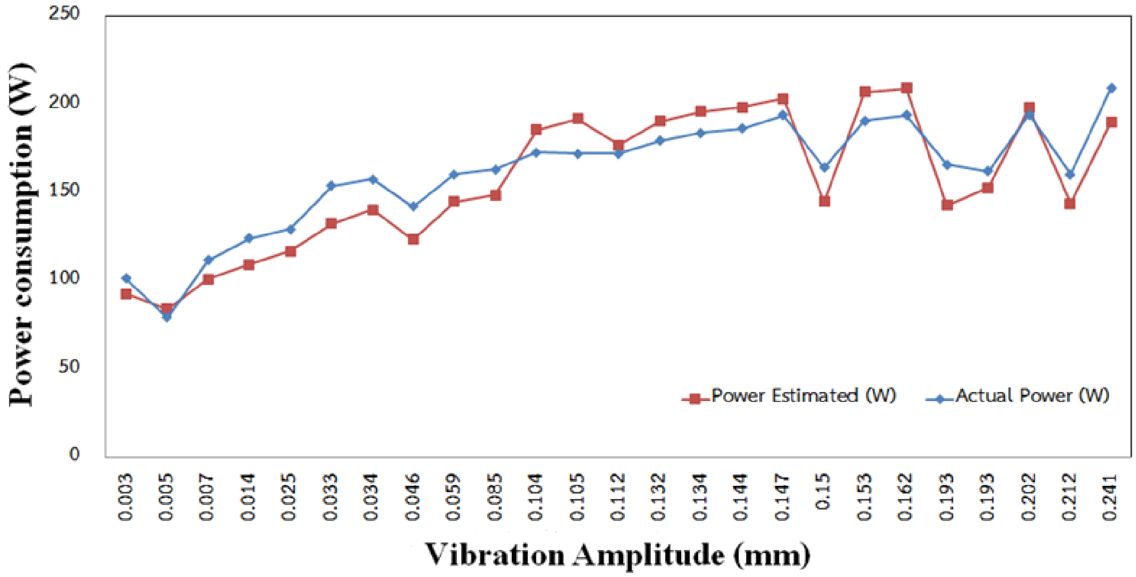

Fig. 12 Comparision of actual power consumption and estimated power consumption model

4. Conclusion

This research deals with the study of vibration diagnoses at various motor speeds. To define energy consumption of induction motor operation by unbalanced mass connected with induction motor. In order to simulate motor operation in mechanical looseness situation. The result shows that if the vibration amplitudes and motor speed are high, then the energy consumption will also be high. Therefore, in this case, it can be concluded that the vibration dianogsis can be a representative of mechanical looseness to predict energy consumption of induction motor by creating the regression model. However, in order to perform the investigation of motor energy consumption, here are some useful recommendations: the vibration measurement has to use highly precise values to smoothly illustrate the energy consumption trend; the vibration effect is a significant factor of motor operation and should be concentrated on.

There are many limitations to this research. Firstly, measurement ranges of the instruments have limited control. Secondly, the experimental setup uses unbalance load constant to be a harmonically varying force but in real situations may be difficult to make the unbalanced load constant. Thus, the regression model in this research can be only guide energy consumption in case of unbalanced load constant operation. For future research, the correlation model of mechanical vibration and energy consumption should be continually studied in real time monitoring cases.

5. Acknowledgment

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6. References

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