Estimating Power Factor of Induction Motors Using Regression Technique

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***Abstract*—Induction motors are one of the largest power consumption in electrical systems. Since induction motors are inductive loads, they produce a lot of power quality issue in the electrical systems. Solving the power quality problem, monitoring power factor of induction motors is important because at no load or light load condition power factor is low and consequently low power factor not only provide a penalty charge, but also generates a huge current and losses in the grid systems. To measure the power factor, zero crossing and instantaneous power methods can be used. Both methods require motor voltage and current waveforms at operating times. Those methods may have a huge cost in terms of requiring the motor to be out of service for connecting devices. In this research, regression analysis will be applied to estimate the power factor of induction motor at any loading condition. The results of the proposed method will be compared with the measured power factor of induction motor in order to substantiate the feasibility of the proposed method.**

***Keywords*—induction motors; regression analysis; power factor; estimation; statistics.**

I. Introduction

Power factor is an important element in power systems and it must be monitored in order to improve power quality. The Power factor is angle between voltage and current and also it can be defined as a ratio of input power. Induction motors have significant roles in electrical systems since 40-50% of generated electrical power consumed by induction motors [1]-[2]. Due to this amount of power consumption from induction motors, the power quality will be quite important because induction motors are inductive loads and create a huge power quality problem in power systems.

To improve the power quality, monitoring the power factor of induction motors is important and it must be maintained between 0.85-0.95 or even toward unity. In industrial factories, variation of motor-loads cause the power factor to be changed with different values from no-load to full-load [3]-[4].This changing particularly at light-load makes a low power factor. The Low power factor produces a huge current and also a voltage drop in the systems [5]. To prevent this issue, the utility company requires maintaining the power factor to the suitable value by customers otherwise charge will be applied for the low power factor [6]-[7]. Therefore, the value of power factor of induction motors must be monitored to design the size of capacitor and improve the power factor to the desired value. To monitor the power factor of induction motors, two methods can be applied [8]. One is the zero crossing method which is required motor current and voltage and also a zero crossing sensor to detect the distance between both waveforms. In the second method, instantaneous power is required to measure average power and then using the formula to obtain the power factor [9]-[10]. Those methods may have a huge cost in terms of connecting measurement devices as the motors have to be switch off.

The estimation techniques can be a good solution to determine the power factor of induction motor at any loading condition [11]. In this research, regression analysis is used to estimate the power factor properly and then the obtained results compare with the method using only measured current and manufacturer data (MCM) [10]. The measured current method needs nominal current from nameplate of the motor and measured current from no-load to full-load.

The regression method only needs a few measured points of the current and the power factor as input data and also the value of nominal current for calculating the motor load. The input data including the power factor and current are measured once by a power factor meter synchronously. Then, the measured data build a model to the regression and the regression provides an estimated carve to the simulated model. Consequently, by such technique, the unknown value of the power factor can be estimated [12]-[13].

Monitoring of the power factor is more important than the current of the motor in order to compensate the power factor and solve the power quality problem [14]-[15]. In this paper, regression analysis with polynomial function will be explained. Then, the result of the proposed method is going to be compared with a method using only measured current and manufacturer data [10] and Kriging method [15].

The paper structure is as follows: section two presents the regression analysis. Section three presents the experimental study. The result of those methods will be presented in section four. Finally, the conclusions are presented in section five.

A. *Power Factor behaviour based on motor load*

Motor load has a substantial role on behaviour of the power factor at operating time. Particularly at no-load or light-load condition, the stator current is provided for friction and windage loss. Since these losses are small, the current and the load are small. However, as the motor is more inductive and magnetizing reactance is required in terms of presence of air gap in the motor, the majority of motor current consumes in magnetizing reactance that is named magnetizing current I_m. Consequently, the no-load current legs the stator voltage by the angle of θ_0 in the range of $75-85^{\circ}$. The Power factor of stator at no-load will be approximately between $0.1-0.3$. In addition, as the motor load rises, its slip increases and therefore the rotor current increases that cause the power factor of stator improves about $0.8-0.9$ of the full-load [9].

II. Regression Analysis

Regression is a statistical method used for fitting linear and nonlinear models. Regression describes a relationship between the independent variable *x* and the dependent variable *y* and it provides a model by nth degree polynomial. Using regression model, two main parts are quite necessary. The first one is considering observed values in order to simulate a model to the regression and the second one is predicting coefficients of polynomial. This can be observed as:

$$y_i = \sum_{i=1}^{n} \mathrm{f}(\mathrm{x_{i,}}\beta) + \varepsilon_\mathrm{i} \tag{1}$$

$$\widehat{y_i} = \mathrm{f}(\mathrm{x_i}, \beta) = \beta_0 + \beta_1 \mathrm{x}_1 + \beta_2 \mathrm{x}_2^2 + \cdots + \beta_\mathrm{m} \mathrm{x}_n^m \tag{2}$$

where in (1) y_i is observed dependent variable. $\mathrm{f}(\mathrm{x_{i,}}\beta)$ is a main function of polynomial which also can be indicated as a predicated values $\widehat{y_i}$. ε_i are errors between observed and estimated values. In (2), $(\beta_0, \beta_1, \beta_2, \ldots \beta_m)$ are the coefficient of polynomial where m shows the number of coefficient. The coefficients $(\mathrm{x}_1 + \mathrm{x}_2^2 + \cdots \mathrm{x}_n^m)$ are independent variables where m and n are number of polynomial degree and number of variables respectively. In (1), when β multiplied by $x_{i,}$, the output will be as $\widehat{y_i}$ which is not as the same as y_i . The difference between y_i and $\widehat{y_i}$ is the MSE ε_i. Now, by having the value of β and ε_i with new set of x_i, the values of y_i will be obtained. Therefore, (1) and (2) can be expressed in a matrix from as shown in (3).

$$[Y] = [X][\beta] + [\varepsilon] \tag{3}$$

where [*Y*] is n-by-1 vector of dependent variables, [*X*] is n-by-m matrix of estimators (Vandermonde matrix), with one column for each estimator and one row for each observation. [*β*] is a m-by-1 vector of unknown parameters to be predicted. *f* is the function of [*X*] and [*β*] which evaluates each row of [*X*] among with the [*β*] vector in order to predict the corresponding row of *y*. [*ε*] is an n-by-1 vector of independent and indicate error between observed and estimated values. Least square procedure is used to minimize the residuals and choose the best fit as shown in (4). Therefore, the vector of polynomial regression coefficients can be estimated in (5).

$$\mathrm{SSE} = \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{y_i} - \widehat{y_i})^2 \tag{4}$$

$$\beta = (\mathrm{X^T X})^{-1} \mathrm{X^T Y} \tag{5}$$

In polynomial regression method, the polynomial degrees have significant roles in terms of fitting the linear and nonlinear models. The polynomial degrees is defined if the polynomial degree is (n =1), it represents a linear model. If polynomial degree is (n =2, 3), it indicates nonlinear models as quadratic and cubic models respectively. As a result selection of polynomial degree can be an effective solution for non-linear models [10].

III. Experimental Study

As it can be seen from Fig. 1, an experimental setup is required using a three phase squirrel cage motor and a DC generator called a dynamometer. In this setup, a volume button named constant speed and torque on Feedback instrument panel 68-441 (connected to the dynamometer) is used to control the motor load [11]. The volume button is connected to a resistance load of the dynamometer that changes the volume to each step. As a result, the loaded dynamometer emulates a mechanical load torque to the motor that affect the motor load to be changed from no-load to full-load condition. The specification of the considered three phase squirrel cage motor is therefore shown in Table I.

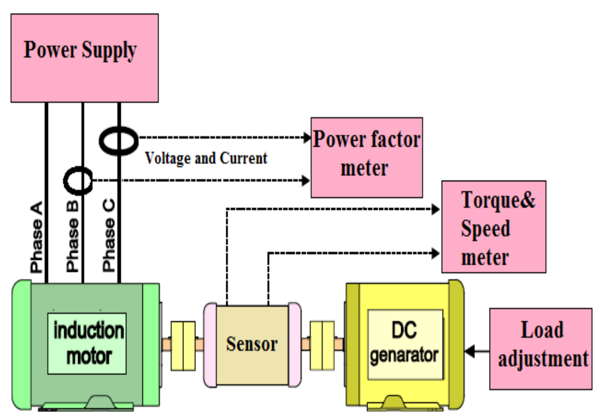

Fig. 1. Experimental setup [12]

TABLE I
Specification of Three Phase Squirrel Cage Motor

Nominal Voltage	380 V/50 Hz
Nominal Current	0.6 A
Rated Power	250 W
Rated Speed	2770 RPM
Rated Power Factor	0.8
Nominal Efficiency	0.72

Torque and speed sensors located in the coupled shaft provide observation of speed and motor torque. These may not be applicable in this case. The only important device will be power analyser for evaluating and measuring the voltage, current, and the power factor from no-load to full-load condition.

The aim of this experimental procedure is to measure the power factor from no-load to full-load condition, particularly at any possible load factor. As measuring the power factor at any load factor is quite necessary, load factor will be calculated as fallows:

$$Load\ factor = \frac{P_i = \sqrt{3}\ \times V \times I\ \times PF}{P_{ir}} \times\ 100\% \qquad (6)$$

$$P_{ir} = \frac{hp \times 0.7475}{\eta_n} \qquad (7)$$

where P_i is input power in W. V is the RMS voltage in three phases line-to-line. I is the RMS current in three phases and PF is power factor of motor, and P_{ir} is input power at full-rated load in W. hp is Nameplate rated horsepower. η is the efficiency at full-rated load [13].

Based on the calculated values of load factor from no-load to full-load condition, there is an attempt to measure the power factor based on those values. The reason why load factor is used instead of motor torque is because using load factor is simpler than using torque sensor. In addition, the load factor performs better as voltage and input current of the motor involved.

Fig. 2 shows the measured components including active current, reactive current and the power factor of a three phase induction motor from no-load to full-load condition. By considering the measured values from no-load to full-load, the load factor is determined by (6) and (7) using 32 points. Then, the power factor is considered on those load points.

Therefore, as the power factor against the motor load is nonlinear, an estimation technique has become important in order to determine the value of power factor at any point of loading. In this case, the regression technique is used to solve the nonlinear model.

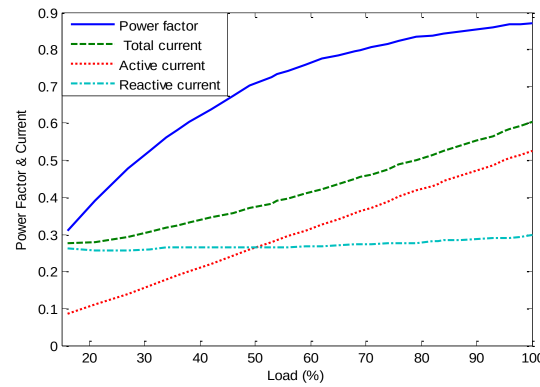

Fig. 2. Currents and power factor measurement

From Fig. 2, it can be understood that the power factor is poor at no-load or light-load condition because at no-load condition, the active current is approximately zero and the motor only consumes reactive current due to magnetic field. By increasing the load, active current will be increased and the power factor also increased. Therefore, due to having no-load or light-load condition at operating time of motor, the power factor should be detected in order to improve the power quality. Because of this issue, monitoring of the power factor has been required by measurement devices. Indeed, using such devices to monitor of the power factor create a high cost for maintenance of devices and turning off the motor for device connection. Therefore, estimation methods in particular regression technique are a low cost solution to determine the power factor at any loading condition.

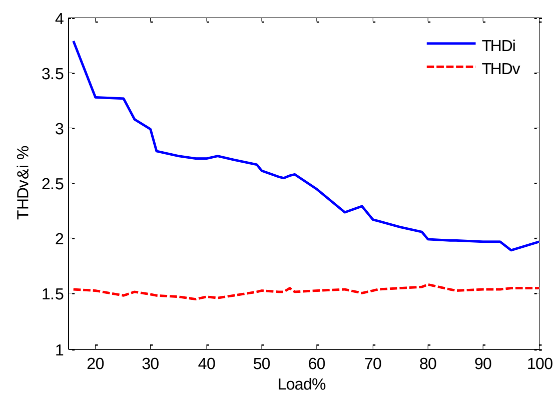

Fig. 3. THD measurement of voltage and current

Fig. 3 indicates that the total harmonic distortion (THD) of voltage (THD*v*) and current (THD*i*) from no-load to full-load condition where *THDv* provided a small changing from no-load to full load condition. However, by increasing the load toward full- load, *THDi* decreased from 3.7% to 1.9%. Consequently, if the induction motor works at full-load, the *THD* and the power factor will have satisfied values. Indeed, since most of the induction motors in industrial are not working at full-load condition, power factor and *THD* has become important due to the power quality improvement. The power factor comes from multiplying of power factor displacement and power factor distortion. The power factor displacement known as a cosine angle of fundamental voltage and fundamental current waveforms and the power factor distortion is related to *THDv* and *THDi* waveforms [20]. In reality, in this case, the power factor is equal to the cos(ϕ) as the both THD voltage and current are quite small. In order to improve the power factor (cos(ϕ)), the value of *cos(ϕ)* at any loading condition is necessary. In this case, the regression method considered a few initial values as training, and then predicted the unknown value of the power factor or *cos(ϕ)* at any desired loading condition based on the simulated model.

IV. RESULTS AND DISCUSSIONS

Regression analysis is a statistical method and it works based on the relationship between the independent variable x and the dependent variable y. Polynomial function is more applicable in regression method due to its flexibility. In polynomial function, the selection of orders is quite important to obtain the value of power factor in high accuracy. In this method a few value of power factor and load against each other are necessary for input of regression. Then, to estimate the values of unknown power factor, regression analysis required creating a model that being fit to the set points (main model). Polynomial coefficients with selecting an order determine this fitting. A great fit causes the unknown points become more accurate. In this case, polynomial regression is applied within third orders. The obtained coefficients at each order indicate in Table II.

TABLE II
POLYNOMIAL COEFFICIENTS OF ORDERS

Orders	β_1	β_2	β_3	β_4
1st order	0.0063	0.3222	-	-
2nd order	-0.0001	0.0171	0.0781	-
3rd order	0.0000	-0.0002	0.0240	-0.0182

In this case, *polyfit* function from Matlab is used to obtain the coefficients. Then, the *polyval* function is used to predict the desired values. Therefore, the results showed that the *polyfit* and *polyval* techniques are a good solution to determine and predict the coefficients of the polynomial and unknown value of the power factor [14]. Hence, using this technique provide a high performance and helped enhance the flexibility and reliability of polynomial regression for the different case studies. Indeed, to provide high accuracy in estimation values, the residual errors of set points data determine how the unknown estimation points can be more accurate.

Figs. 4-6 present the measured power factor curve (set points) and estimated power factor curve (set points) within 1^{st}, 2^{nd} and3^{rd} with residual error of 0.033, 0.001 and 1.304E-04.

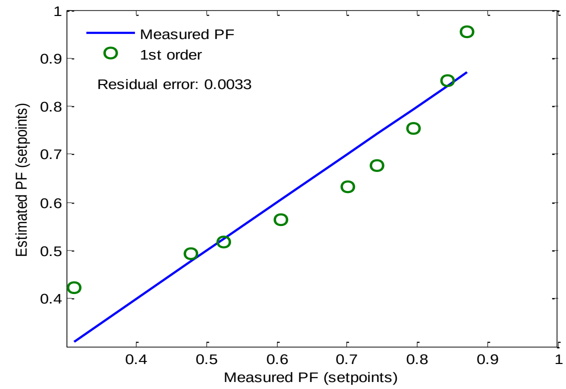

Fig. 4. The residual errors of polynomial regression in 1st order

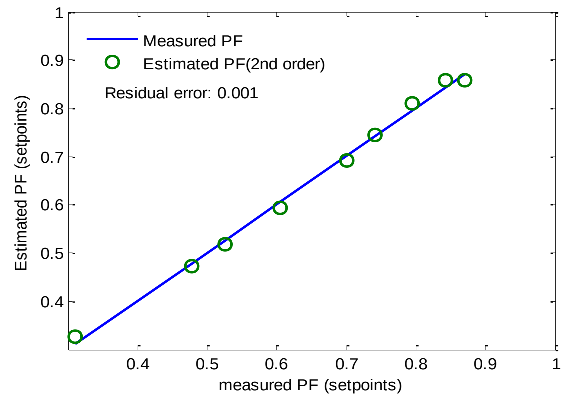

Fig. 5. The residual errors of polynomial regression in 2nd order

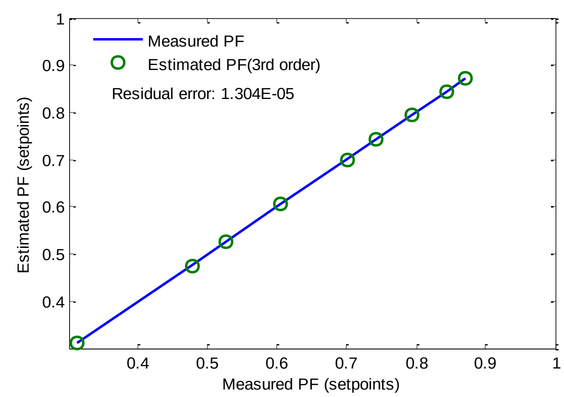

Fig. 6. The residual errors of polynomial regression in 3rd order

From Figs. 4-6, it can be understood that while the polynomial order increases the residual error reduces. For instance, in IM 250W, polynomial regression with 3^{rd} order performed a high fit with a small residual error compare with 1^{st} and 2^{nd} order. Therefore, it means that 3^{rd} order fitted exactly and now with this model the unknown power factor points can be estimated accurately.

TABLE III
ESTIMATION RESULTS (PF) OF DIFFERENT METHODS

Estimation models		Estimation errors		
		MSE	*RMSE*	*MAPE*
Method using measured current		4.05E-04	0.0201	2.7479
Kriging method[8]		2.63E-05	0.0051	0.5764
Regression method	1st order	0.0023	0.0481	6.3848
	2nd order	1.02E-04	0.0101	1.2880
	3rd order	**9.27E-06**	**0.003**	**0.3822**

Table III indicated the estimated power factor at every 10 percent of motor load through three methods. The measured current method (MCM) in [10] obtained an error at each loading condition. To minimize this error, the study found estimation methods with high performance including Kriging method that described in [8] and regression method for the power factor estimation. Hence, the comparison results observed that regression with 3rd order estimated the power factor at desired loading condition with low error.

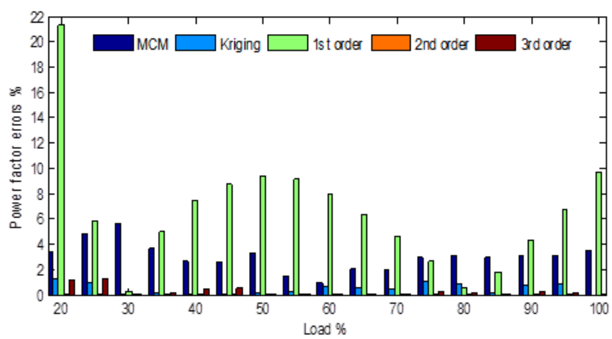

Fig. 7. Error estimation of considered methods from no-load to full-load

From Fig. 7, the estimated errors present that the method using only measured current and manufacturer data (MCM) produced significant errors due to variation of reactive current from no load to full load. In this method, the estimated errors are more than 2 % at most of loading points. However, results of Kriging method provided errors less than 2% compare with MCM. In the regression method, although the first order provided high errors more than 2% in most loading points compare with other methods, second and third orders produced very small error less than 1% in particular third order that indicated a high accuracy .

Table IV presents the three performance measure of MSE, RMSE and MAPE in the five models.

TABLE IV
ESTIMATION ERRORS OF DIFFERENT METHODS

Load %	Measured PF	MCM	Kriging method	Regression		
				1st	*2nd*	*3rd*
20	0.370	0.357	0.375	0.449	0.382	0.375
30	0.514	0.485	0.513	0.512	0.507	0.514
40	0.622	0.639	0.623	0.576	0.613	0.625
50	0.705	0.729	0.707	0.639	0.700	0.707
60	0.763	0.770	0.758	0.702	0.768	0.762
70	0.803	0.818	0.798	0.766	0.819	0.801
80	0.834	0.861	0.827	0.829	0.850	0.832
90	0.855	0.881	0.848	0.892	0.863	0.858
100	0.871	0.902	0.871	0.956	0.858	0.872

From Table IV, the method using measured current and manufacturer data demonstrated a poor result with an error in 2.7479%. However, regression and Kriging methods provide the better results where the polynomial regression with third order has shown a great output result with small error in 0.3822% and Kriging in 0.5764% respectively compare with first and second orders.

CONCLUSIONS

This paper examined the polynomial regression techniques in order to estimate the power factor of induction motor at any loading condition. As a result, the polynomial regression with third order performed very well with much less error than the method using measured current and Kriging method. Despite the accuracy of the Kriging model being approximately similar to the third order of polynomial regression, the polynomial regression can be more reliable in other cases due to possibility of selecting different degrees. In the feature, a large induction motor will be applied in order to verify the accuracy of proposed method.

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