Determination of Three-Phase Induction Motor Equivalent Circuit Parameters Experimentally

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ABSTRACT

Three-phase induction motors are the most widely used motors and they absorb the largest electrical power among electrical loads. To know the conditions and performances of the motor, it requires the values of its equivalent circuit parameters. At this time, there have been found many methods to determine such parameters, but for most practitioners, those methods are still not suitable for their needs in the field due to the complexity and the lack of resources reasons. This paper proposes a simpler test and estimating methods to determine the values of circuit parameters. It demonstrates how the experiments and calculations of parameters are conducted. The experiments were conducted in a laboratory and two of the most popular equivalent circuit models (original and simplest models) were tested. The experiments used a three-phase induction motor of 5.5 kW, 380 V. The results show that the experimental method proposed could give accurate data to determining the equivalent circuit parameters. The simplest model equivalent circuit (L-Model) is able to provide accurate results and therefore, it is recommended to be applied in the fields.

Keywords: *conditions and performances, original and simplified models, accuracy, practitioners, electric machines*

1. INTRODUCTION

Three-phase induction motors are electric machines the most widely used in industries due to its excellence (Ryff, 1994) (Tezcan et al., 2018). The equivalent circuit of an induction motor and the value of its parameters are very important to be understood by field practitioners who will analyze and evaluate the motor conditions and performances. Pappano has started with a model-based mapping identification concept (state-space identification scheme) used to identify the parameters of induction motors using transient dynamics (Pappano et al., 1998) and used integral calculation methods while (IEEE Std, 2004) used experimental methods for the same purposes. In (Yoo et al., 2015) it is explained how the values of equivalent circuit parameters are determined experimentally.

Carlos considers that such a method in (IEEE Std, 2004) is too difficult to be implemented in the field due to the complexity of the method and lack of resources. Due to this, Carlos proposed to use a data catalog from the manufacturer to determine such parameters without any experiment (Wengerkeivicz et al., 2017). Wu has proposed another method by means of a polynomial regression which confirms that the theoretical impedance characteristic of an induction machine can be expressed in the form of a polynomial fraction and the parameters can be obtained with a single count (Wu et al., 2018). These last proposed methods require a high level of mathematics (Pappano et al., 1998) which is generally not preferred by practitioners.

Salimin has estimated its equivalent set parameters using Matlab-Simulink simulation even based on machine test result data (Salimin et al., 2013). Different from other authors, Anthony is more interested in the equivalent circuit rather than the methods. He proposed a new equivalent circuit which is simpler than conventional circuits by intention to simplify it and more applicable [9].

Regarding equivalent circuits, (Tezcan et al., 2018) and (Fischer, 2013) set them to three equivalent circuit models, namely: the original model (T), intermediate simplified model (IEEE), and the simplest model (L).

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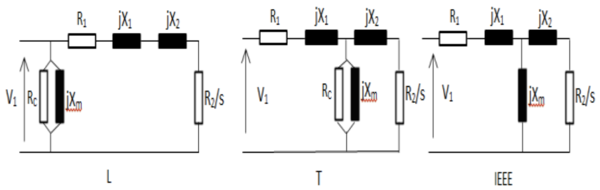

Figure 1. The three models of equivalent circuit parameters (L, T and IEEE models)

The L-Model, the simplest circuit model was derived to meet the simplicity of analyses. Simplification is done by neglecting voltage drop across stator impedance and the active current flowing through the core. Furthermore, neglecting the core loss is referred to Rajinder et al., 2018. On one side it will reduce the complexity of analyses, but on another side, its accuracy becomes doubtful. Actually, the accuracy will be very doubt for a motor which has no-load current quite big (30-80% of nominal current) while it does not matter for transformers. Not only these, for the sake of simplicity in implementation, Fan also proposed a T-model circuit equivalent used to deduce the relationship between induction motor port impedance and internal parameters including stator inductance, rotor inductance, magnetizing inductance and rotor resistance (Fan et al., 2014).

In this paper, the authors propose a simpler experimental method than the one in IEEE 112 and verify the accuracy of the simplest circuit model (L-Model) compared to the original one (T-Model) to get an idea of how they are different or meet each other.

1.1. Motor equivalent circuits

Three-phase electric machines are always designed in a balanced system, as well as electric motors. Therefore, the equivalent circuit is always illustrated as one phase only (Selek et al., 2017).

The equivalent circuits of induction motors are shown in Figures 2, 3 and 4 which are similar to the ones mentioned in (Tezcan et al., 2018).

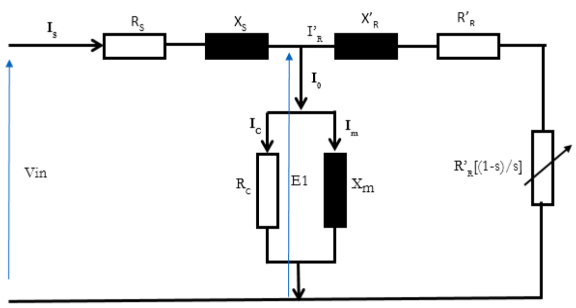

Figure 2. Induction Motor equivalent circuit (original)

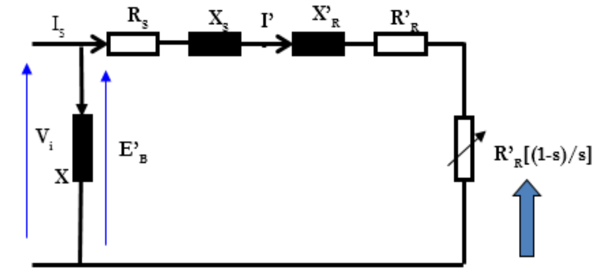

Figure 3. Induction Motor equivalent circuit (simplified)

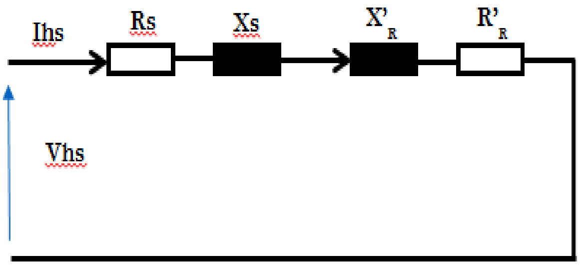

Figure 4. Short circuited Induction Motor equivalent circuit

For induction motors, it applies:

$$I_0 = I_C + jI_m \quad (1)$$

$$P_{cus} = m.I_s^2.R_s \quad (2)$$

$$P_{fe} = m.I_C^2.R_{fe} = \frac{E_1^2}{R_{fe}} \quad (3)$$

where: P_{cus} = stator copper loss, P_{fe} = core loss, m = phase number.

The rotor copper loss (P_{CUR}) and mechanical power of rotor (P_R) are:

$$P_{inR} = I^2\frac{R_R}{s} \quad (4)$$

$$P_{CUR} = I_R^2 R_R \quad (5)$$

$$P_R = I_R^2 R_R \frac{1-s}{s} = P_{inR}(1-s) \quad (6)$$

where P_{inR}= input power to rotor.

The mechanical power (P_R) is expressed as R_R [(1-s)/s] including the rotational loss (P_{rot}) experienced by the motor.

According to Eq. 5 and 6:

$$P_R = P_{CUR}\left(\frac{1-s}{s}\right)$$

$$P_{CUR} = P_R\left(\frac{s}{1-s}\right) \quad (7)$$

$$P_{CUR} = P_R\left(\frac{s}{1-s}\right) = sP_{inR} \quad (8)$$

The shaft power of the motor is

$$P_{out} = P_R - P_{rot}$$

(9)

The motor torque can be calculated as:

$$P_{out} = T.\omega \quad (10)$$

$$T = \frac{P_{out}}{\omega}; \quad (11)$$

or

$$T = \frac{P_{out}60}{2\pi n_r} = 9{,}55\frac{P_{out}}{n_r} \text{ Nm} \quad (12)$$

So, with the well-known parameters of the equivalent circuit of the motor, the motor indicator performances can be calculated.

2. METHODOLOGY

The motor used in this research is a **Three-phase Wound Rotor Induction Motor**: 5.5 kW, 380 V, 7.6 A, 0.84, 2840 rpm and 50 Hz. The motor is connected in star (Y), 3 wires and the rotor windings are short-circuited as shown in Figure 5.

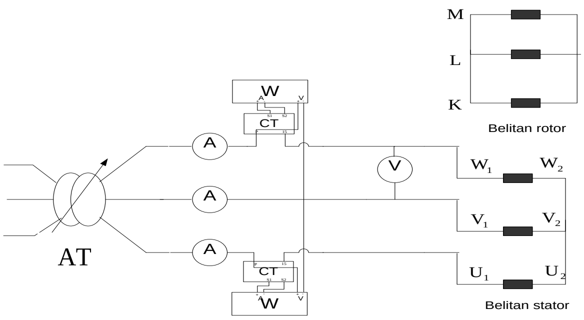

Figure 5. Experiment circuit diagram

2.1. Data retrieval through experiments

For data retrieval, to get accurate results, the measuring instruments must be accurate. In this case, industrial standard instruments are used such as voltmeters and ammeters class 1 for dc and class 2 for ac, and class 1 wattmeters.

To determine the equivalent circuit parameters can be done by simply three tests, namely: stator winding measurement, no-load test and short circuit test (*blocked rotor*).

Stator winding resistance measurements: using V-A DC method as recommended by (IEEE Std 118, 1992). This measurement is intended to obtain a stator resistance value (R_S). Measurements are performed at least three times with a current of about 10% of the motor's nominal current. The result is taken from the average values. For the sake of simplicity, skin effects and temperature corrections are not included.

No-load test: The no-load test is intended to determine mechanical losses (P_{rot}), core losses (P_{fe}) motors in steady-state conditions and parameter values: Core resistance (R_C) and magnetic reactance (X_m). In this experiment, the rotor was free running with a source voltage varied from 60-100% of the nominal voltage. With these voltages, the motor is assumed at a nominal and constant speed. The measured parameters are no-load current (I_0), no-load power (P_0) and no-load voltage (V_0).

Short circuit (*blocked rotor*) test: This experiment is intended to determine the stator leakage reactance (X_S) and rotor (X'_R) as well as rotor resistance (R'_R). In this experiment, the motor is kept stop (*blocked*). Then the voltage is increased gradually from zero to a certain small value (be careful because the short-circuit voltage is very small) until the obtained short circuit current is equal to the motor nominal current. The measured parameters are the short-circuit current (I_{SC}), the short-circuit power (P_{SC}) and the short-circuit voltage (V_{SC}).

2.2. Equivalent parameters calculation

There are two equivalent circuit models used in this calculation, i.e. the original model (T-Model) and the simplest model (L-Model).

First of all is to calculate P_{cuS}, P_{fe} and P_{rot}. $P_{fe}+P_{rot} = P_0-P_{cuS}$ and P_{fe} and P_{rot} are separated graphically with some tricks. Since the rpm of the motor is relatively constant, P_{rot} is also constant, then P_{fe} can be found. From P_{fe}, R_c and Xm are calculated. X_S, R'_R and X'_R are calculated from short circuit test where $X_S = X'_R$ and R'_R is calculated from P_{sc} together with R_S.

2.3. Model accuracy check

Based on both circuit models (T and L) the results of calculations are compared to see the extent of differences, how the results are applied to analyze motor performances. After that, the comparison is then continued with how the calculation results are fit with the technical specifications of the motor (name-plate). If the L-Model is capable of delivering quite accurate results, then that model will be proposed to be applied for reasons of its simplicity in the analysis.

3. RESULTS AND DISCUSSION

3.1. Determination of R_S, P_{fe} and P_{rot}

From the measurement of the stator winding resistance the obtained R_S is 1.47 Ω. In the no-load motor test, it applies: $P_{ins} = P_{cus} + P_{fe} + P_{rot}$ where: P_{ins} = Power input stator (W); P_{cus} = stator copper loss (W); P_{fe}= Core loss (W) and P_{rot} = rotational loss (W).

The measured power in this experiment is P_{ins}. $P_{cus} = 3.\ Is^2.Rs$ can be computed from the experimental data, then the $P_{fe}+P_{rot}$ loss can be known. It needs a special trick in determining/separating these two losses. To determine the P_{rot} is done through the plotting of

$(P_{fe}+P_{rot}) = f\,(V_0)$, linearizing $((P_{fe}+P_{rot}) = f\,(V_0/V_n)^2$ and interpolating of the curve until cutting the power axis. This intersection point is P_{rot} at nominal motor rpms as shown in Figure 6. From the linearization curve acquired P_{rot} = 120 W. Then plotting them back together as the curve $(P_{fe} + P_{rot}) = f\,(V_0)$ as shown in Figure 7. It is seen that the P_{fe} changes quadratically against V_0 and at nominal of V_0, P_{fe} = 58,3 W.

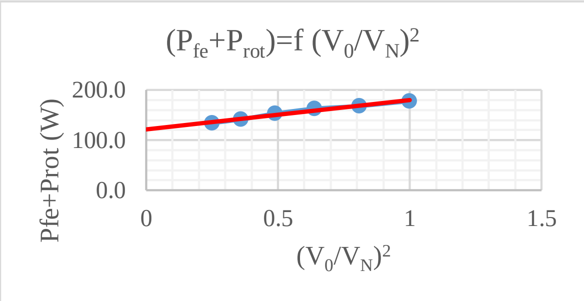

Figure 6. Linierization curve Pfe + Prot = f $(V_0/V_N)^2$

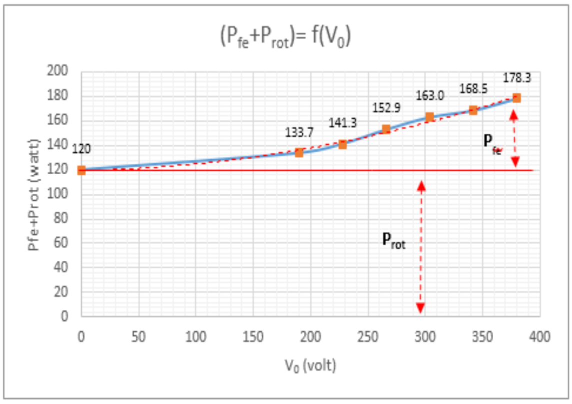

Figure 7. The curve of $(P_{fe}+P_{rot}) = f\,(V_0)$

3.2. Determination of parameters based on L-Model

From the curve in Figure 7, P_{fe} = 58.3 W, the voltage drop at the stator impedance was ignored, then from the no-load test obtained:

$$R_c = \frac{V_{in}^2}{P_{fe}} = \frac{(380/\sqrt{3})^2}{58{,}3/3} = 2477\ \Omega$$

$$I_c = \frac{V_{in}}{R_c\sqrt{3}} = \frac{380}{2477\ \sqrt{3}} = 0{,}09\ A$$

$$I_m = \sqrt{I_s^2 - I_c^2} = \sqrt{6{,}33^2 - 0{,}09^2} = 6{,}27\ A$$

$$X_m = \frac{V_{in}}{I_m\sqrt{3}} = \frac{380}{6{,}27\sqrt{3}} = 35\ \Omega$$

In the short circuit test the short circuit current is limited up to the motor nominal current:

V_{SC} = 56,5 V, I_{SC} = 12,23 A and P_{SC} = 746,3 W.

$$P_{CUS} = 3 I_{SC}^2 R_S = 3\ * 12{,}23^2 * 1{,}47 = 659{,}61\ W$$

$P_{fe} = \frac{V_{SC}}{V_n} P_{fe\ Vn} = \frac{56{,}5}{380} * 58{,}3 = 8{,}67\ W$ (assumed linear)

$P_{CUR} = 746{,}3 - 659{,}61 - 8{,}67 = 78$ W or 26 W/phase

Since the value of P_{fe} is just about 1% of total P_{SC}, then the current flowing into the core is negligible. Therefore, the current flowing into the R'_R is the same as the stator, namely I_{SC}= 12,23 A,

so, $$R'_R = \frac{P_{CUR/F}}{12.23^2} = \frac{26}{12.23^2} = 0{,}17\ \Omega$$

$$Z_e = \frac{V_{hs}}{\sqrt{3} * I_{hs}} = \frac{56{,}5}{\sqrt{3} * 12{,}23} = 2{,}67\ \Omega$$

Dengan Rs = 1,47 Ω

$$X_e = \sqrt{Z_e^2 - R_e^2} = \sqrt{2{,}67^2 - (1{,}47 + 0{,}17)^2} = 2{,}11\ \Omega$$

$X_e = X_S + X'_R$ and $X_S = X'_R$

So, R_C = 2477 Ω and X_m = 35 Ω. This shows how small X_m compared to the R_C, therefore, I_C is much smaller than I_m and can be ignored as well.

In short circuit analysis an assumption was taken that P_{fe} and I_0 are ignored, so, all stator currents flow to the rotor.

$$R_e = \frac{P_{hs}}{3\ I_{hs}^2} = \frac{746{,}8}{3 * 12.33^2} = 1{,}66\ \Omega$$

$$R'_R = R_e - R_s = 1{,}66 - 1{,}47 = 0{,}19\ \Omega$$

$$Z_e = \frac{V_{hs}}{I_{hs}} = \frac{56{,}5}{12{,}33\ \sqrt{3}} = 2{,}65\ \Omega$$

$$Z_e = \sqrt{R_e^2 + X_e^2}$$

$$X_e = \sqrt{Z_e^2 - R_e^2} = 2{,}06\ \Omega$$

$$X_e = X_s + X'_R;$$

$$X_s = X'_R = 1{,}03\ \Omega$$

Thus, the parameters that have been found: R_s = 1.47 Ω, $X_S = X_R'$ = 1.03 Ω, R_R' = 0.19 Ω, R_c = 2477 Ω, and X_m = 35 Ω as can be seen in Figure 8.

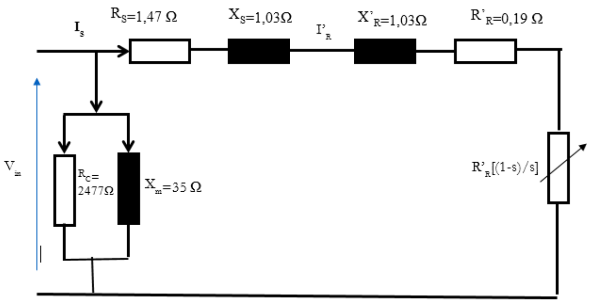

Figure 8. L-Model equivalent circuit parameters values

3.3. Determination of parameters based on T-Model (original).

In this analysis it starts with short circuit test. In this case it applies:

$$P_{SC} = P_{CUS} + P_{CUR} + P_{fe}$$

By the same way as in L-model with ignoring P_{fe} and assuming the current flowing into the R'_R is the same as the stator current I_{SC}= 12,23 A,

so, $$R'_R = \frac{P_{CUR/F}}{12.23^2} = \frac{26}{12.23^2} = 0{,}17\ \Omega$$

$$Z_e = \frac{V_{hs}}{\sqrt{3} * I_{hs}} = \frac{56{,}5}{\sqrt{3} * 12{,}23} = 2{,}67\ \Omega$$

With Rs = 1,47 Ω

$$X_e = \sqrt{Z_e^2 - R_e^2} = \sqrt{2{,}67^2 - (1{,}47 + 0{,}17)^2} = 2{,}11\ \Omega$$

$X_e = X_S + X'_R$ and $X_S = X'_R$

so, $X_S = X'_R = 1{,}05\ \Omega$

Under no load voltage, core loss (P_{fe}) and rotational loss (P_{rot}) are equal to those in the L-Model.

With I_0 = 6,33 A, V_{in0} = 380 V/√3=220 V, R_S = 1,47 Ω dan X_S = 1,05 Ω dan P_0=355 W can be done the following calculations:

$$\cos\varphi = \frac{P_0}{\sqrt{3} * V_{in0} * I_0} = \frac{355}{\sqrt{3} * 380 * 6{,}33} = 0{,}0852$$

$$\varphi = 85{,}11°$$

$$\overline{E_1} = \overline{V_{in}} - \overline{V_{RS}} - \overline{V_{XS}}$$

$$E_1 = 220\ V < 85{,}11° - (I_0 * R_S < 0° + \ I_0 * X_S < 90°)$$

$$E_1 = 220\ V < 85{,}11° - (6{,}33 * 1.4 < 0° + \ 6{,}33 * 0{,}965 < 90°)$$

$$E_1 = 220\ V < 85{,}11° - 9{,}30 < 0° - 6{,}11 < 90°)$$

$$E_1 = 18{,}75 + J219{,}2 - 9{,}30 - J6{,}11)$$

$$E_1 = 9{,}45 + J213{,}09$$

$$E_1 = 213{,}3\ V\ < 83{,}96°$$

Based on this voltage R_C and X_m can be known:

$$R_c = \frac{E_1^2}{P_{fe}} = \frac{213{,}3^2}{58{,}3/3} = 2341\ \Omega$$

$$I_C = \frac{213{,}3}{2341} = 0.09\ A$$

$$I_m = \sqrt{6{,}33^2 - 0{,}09^2} = 6{,}33\ A$$

$$X_m = \frac{213{,}3}{6{,}33} = 33{,}70\ \Omega$$

Thus, the parameters determined by using T-Model are found as: X_S = X_R' = 1,05 Ω, R_R' = 0,17 Ω, R_C = 2341 Ω, X_m =33,70 Ω as shown in Figure 9.

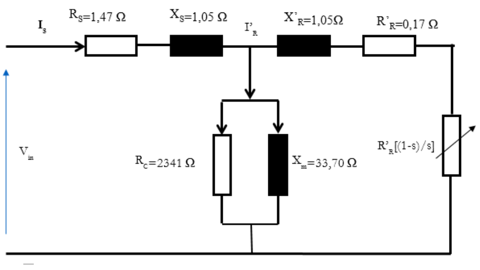

Figure 9. T-Model equivalent circuit parameters values

3.4. Comparison between two models results

To know how the calculation results from both models compared to each other, the parameters' values of both models are presented in Table 1. From this table, it is clear that both models give different results. Some values of L-Model are higher and some are lower than those of T-Model: R_R', R_C and X_m are higher, while X_S and X_R' are lower.

Now, they will be treated for predicting motor performances. By using the calculated parameters' values, some motor performance parameters will be predicted based on actual running motor under loads from minimum to nominal loads. In this case, there are two parameters are analyzed, which are the efficiency and torque as presented in Table 2.

It is seen clearly that both models give almost the same results. The difference in efficiency just 0.1% and torque only 0.02 Nm or 1%. This is prove that the circuit L-Model is as accurate as the original one.

If it is compared to the motor's name-plate, the results obtained from the experiment provide the nominal load powers 5504.8 W and 5510.9 W for the L and T models respectively at the speed of 2855 rpm. On the motor name-plate, it is written that rated power = 5.5 kW and rated speed = 2840 rpm. These are proves that they are almost the same and matched each other. This tells that the equivalent circuit L-Model is capable to give accurate results as the original one, even there are many simplifications.

Table 1. Comparison of parameter values calculation results

NO.	PARAMETERS	L-Model	T-Model	Δ (L-T)	
		Ω	Ω	Ω	%
1	R_S	1.47	1.47	0	0.0
2	R_R'	0.19	0.17	0.02	11.8

3	X_S	1.03	1.05	-0.02	-1.9
4	X_R'	1.03	1.05	-0.02	-1.9
5	R_C	2477	2341	136	5.8
6	X_m	35	33.7	1.3	3.9
	Voltages	V	V	V	%
7	V_{inS}	220	220	0	0.0
8	E_1	220	213.3	6.7	3.1

Table 2. The comparison of the calculation results for efficiency and torque

L-MODEL		T-MODEL		Δ(L-T)	
η_L(%)	T_L (Nm)	η_T(%)	T_T (Nm)	Δη (%)	ΔT (Nm)
52.68	1.31	52.70	1.31	-0.02	0.00
75.36	3.79	75.38	3.80	-0.02	0.00
84.79	8.47	84.83	8.48	-0.04	0.00
86.55	11.61	86.61	11.62	-0.06	-0.01
86.80	14.43	86.87	14.44	-0.07	-0.01
86.32	16.72	86.41	16.74	-0.09	-0.02
86.55	18.42	86.65	18.44	-0.10	-0.02

4. CONCLUSION

The experimental method proposed here is capable to give accurate data for determining the equivalent circuit parameters even with regular instruments and without considering skin effects and temperature corrections. In relation to the circuit models, the simplest model can give accurate results. Therefore, this model is recommended to be applied in fields for its simplicity in the analysis.

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