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An Experimental Study on Performance Determination of Slip-Ring Induction Motor

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Abstract : This paper determines the experimental performance of a slip ring induction motor according to standards when using TERCO equipment. The aim of this study is to present the experimental procedures for determining the performance of a slip-ring induction motor and to demonstrate to researchers how the efficiency of a slip-ring induction machine can be calculated experimentally. The method used for this study is a loss summation method in which a no-load test, resistance measurement test, a direct measurement test, an overload test, and a starting current test were performed to determine the losses in both the rotor and the stator of a slip ring induction motor. The result shows no-load losses of 300 W, the rotor and stator resistances are determined to be 2 Ω and 4.8 Ω, with the resistance losses as calculated being 75.86 W and 0.35 W, respectively. However, the brush resistance losses are determined as 4.12 W with the stray losses in iron and conductor as 14 W. The efficiency of the induction motor is calculated from the measured parameters to be 82%. Besides, the starting current measurements are taken with and without motor resistances at lower voltages where it shows that with higher starting current the voltage without rotor resistance develops higher values.

***Keywords* – Induction motor, No-load losses, Resistance losses, Power Losses, Efficiency**

1. INTRODUCTION

It is known from the market industry that more than half of the electrical energy generated in industrialized countries is converted into mechanical energy by induction motors. Among the different types of induction motors, three-phase squirrel cage induction motors covers more than 90% of electric drives in industries and are more popular (Pjetri, Luga, & Bardhi, November 2015). They can be found from a few hundred watts to several megawatts. Three-phase induction motors are considered the universal workhorses of industry, converting up to 80% of all electrical power into mechanical energy and covering many heavy industrial applications such as fans, blowers, compressors, mixers, conveyors, etc. These motors are robust machines that are used not only for general purposes but also in hazardous areas (R, MohanDass, & S, Septmber 2014). Despite all motor technologies, induction motors remain the most commonly used on the market, especially when variable speed is not required. Minimizing electrical energy consumption through better motor design is becoming a major concern (Saravanan, Sathiswar, & Raja, May 2012). Whether in the home or in industry, controlling a motor is necessary. The systems used for this are called drives. Such a system using electric motors is called electric propulsion. Different sensors and control algorithms are used for electric drives. This is done to control the speed of the motor using the best speed control methods (E., E., Eke, & J., September 2021). Besides, slip ring induction motor is one of the types of 3-phase induction motor and is a wound rotor motor. Due to various advantages such as low initial current, high starting torque and improved power factor, it is used in applications that require high torque, cranes and elevators.

The asynchronous motors are characterized by manufacturer information such as nominal speed, power, voltage, current and efficiency. In the past, the efficiency value was of secondary importance. Nowadays, with the increasing emphasis on energy saving and rising energy prices, the efficiency value has become very important and even dominant for industrial applications. The efficiency values given by the manufacturer are measured or calculated according to certain standards (Renier, Hameyer, & Belmans, September 1999).

One of the industries using induction motors is a steam power plant. The role of induction motors is very important in the operation of steam power plants. Therefore, it is necessary to monitor the performance, stability and efficiency to anticipate disturbances that may cause damage or shorten the life of the induction motor (Syahputra, Purwanto, Wiyagi, Mustar, & Soesanti, June 2021). Minimizing electrical energy consumption through better motor design is becoming a major concern (Saravanan et al., May 2012). However, for an induction motor, total losses consist of copper losses, core losses, and friction and windage losses. There are copper losses and iron losses in the stator and copper losses and friction losses in the rotor. In fact, there are some core losses in the rotor. However, under operating conditions, the rotor frequency is so low that it can be assumed that all core losses occur only in the stator. Induction motor efficiency is determined by loading the motor and directly measuring the input and output (Saravanan et al., May 2012).

1.1 PREVIOUS RESEARCHES

Several methods using different concepts have been used to determine the performance of induction machines. However, others focus on improving the performance of the machine through additional connection or optimization. This section reviews some of the research used in determining the performance of induction machines.

A study on the performance and evaluation of the control of three-phase induction machines with Simulink describes a series of experiments and discusses their results to determine the efficiency of low-voltage three-phase squirrel-cage induction motors (E. et al., September 2021). The measured efficiency of an induction motor connected directly to the mains. Different standards are mentioned and their comparisons are discussed. A short description of the measurement setup is presented and measurement results for engines from several manufacturers with different standards are suggested. The results clearly show the need to be very careful with the efficiency information provided by the manufacturer.

A researched article discusses analysing the performance of an induction motor using the motor current signature analysis technique (Syahputra et al., June 2021). This technique is a reliable technique that can be used to analyse damage to an induction motor. With this technique, the current signal from the induction motor is sensed using a current transformer. The signal is then passed to signal conditioning and then to the data acquisition device. The critical signal data is analysed with insufficient computer equipment. The results of this analysis determine the condition of the induction motor, whether it is normal or damaged. Analysis of several induction motors shows that most are under normal conditions and still operational.

Another publication proposes a novel technique to improve the performance of induction motors. By using a modified stator winding arrangement, the efficiency has been improved by 7% and tested in the laboratory. Experimental results and simulations were presented to validate the results (Saravanan, Azarudeen, & Selvakumar, April 2012).

Furthermore, a simple procedure for estimating the power of three-phase asynchronous motors from a no-load start-up test without speed measurement was investigated (Pereira et al., 2020). The proposed method is validated experimentally through tests on 229 medium-power engines ranging in power from 22 to 90 kW; The estimated performance is then compared to measurements obtained through standardized laboratory tests. The method allows the performance of medium-power induction motors to be estimated with acceptable accuracy through rapid and inexpensive testing with few sensors, making it a potential replacement for expensive and labor-intensive laboratory testing.

This paper determines the experimental performance of a standard slip ring induction machine using TERCO equipment. The determination is related to the total loss method, which proposes a separate measurement of the individual losses.

2. EXPERIMENTAL PROCEDURES AND METHODOLOGY

This section discusses on the experimental procedures and methodology in determining the performance of slip ring induction motor. Besides, the governing equations use for the summation or power losses were presented.

2.1 Experimental Procedures

According to the standards, the efficiency for three-phase motors above 400 W should be determined in relation to the summation of losses method, which implies separate measurement of each loss. However, the losses in an induction motor consist of two divisions. First, load-current-independent losses, which are composed of core losses, friction losses in bearings, ventilation losses, and friction losses in brushes. Second, losses dependent on the load current, which include resistive losses in the primary winding, resistive losses in the secondary winding, brush resistance losses, stray losses in iron parts and stray losses in conductors.

No load test values can be calculated using equation 2.1 to 2.4.

$$P_{om} = P_R + P_T \qquad (2.1)$$

Where P_{om} is the no-load power loss, P_R and P_T are the rotor and stator Wattmeter readings.

$$\tan\varphi = \sqrt{3}(P_T - P_R)/(P_T + P_R) \qquad (2.2)$$

$$I_{2\ rms} = I_2/\sqrt{2} \qquad (2.3)$$

$$R_{mean} = (R_1 + R_2 + R_3)/3 \qquad (2.4)$$

Where R_{mean} is the average readings of each rotor and stator resistances.

Power is measured using the dual wattmeter method and resistance is measured using the volt-ammeter method, which are assumed to be known. The resistive losses in a three-phase winding are given by equation 2.5, regardless of the circuit.

$$P_{cuo} = \left(\frac{3}{2}\right) \cdot R_u \cdot I^2 \qquad (2.5)$$

Where R_u equals the resistance measured between two tapping's of the three phase winding, also determined from equation (2.4), and I = one of the equal line currents.

The actual no-load losses, P_0 are calculated using equation 2.6.

$$P_0 = P_{0m} - P_{Cu0} \qquad (2.6)$$

The resistances for the stator and rotor at 75℃ can be obtained using the relation of equation 2.7.

$$R_{75} = \frac{310}{235 + t} \cdot R_t \qquad (2.7)$$

Where the temperature t in the measurement is assumed to be 20℃

The resistance losses in stator and rotor at rated current are determined using equation 2.8.

$$P_{Cum} = \frac{3}{2} \cdot R_{u75} \cdot I^2 \qquad (2.8)$$

Brush resistance losses are calculated from the result using the expression in 2.9

$$P_{brush} = 3 \times 0.3 \times I_{2n} \qquad (2.9)$$

Where 0.3 is the voltage drop in brush and I_{2n} is the rotor current at rated load.

Stray losses in iron and conductors together is given by equation 2.10.

$$P_{stray\ loss} = 0.01 \times P_n \qquad (2.10)$$

Where P_n = output power of the machine at torque 7.5 Nm from direct measurement

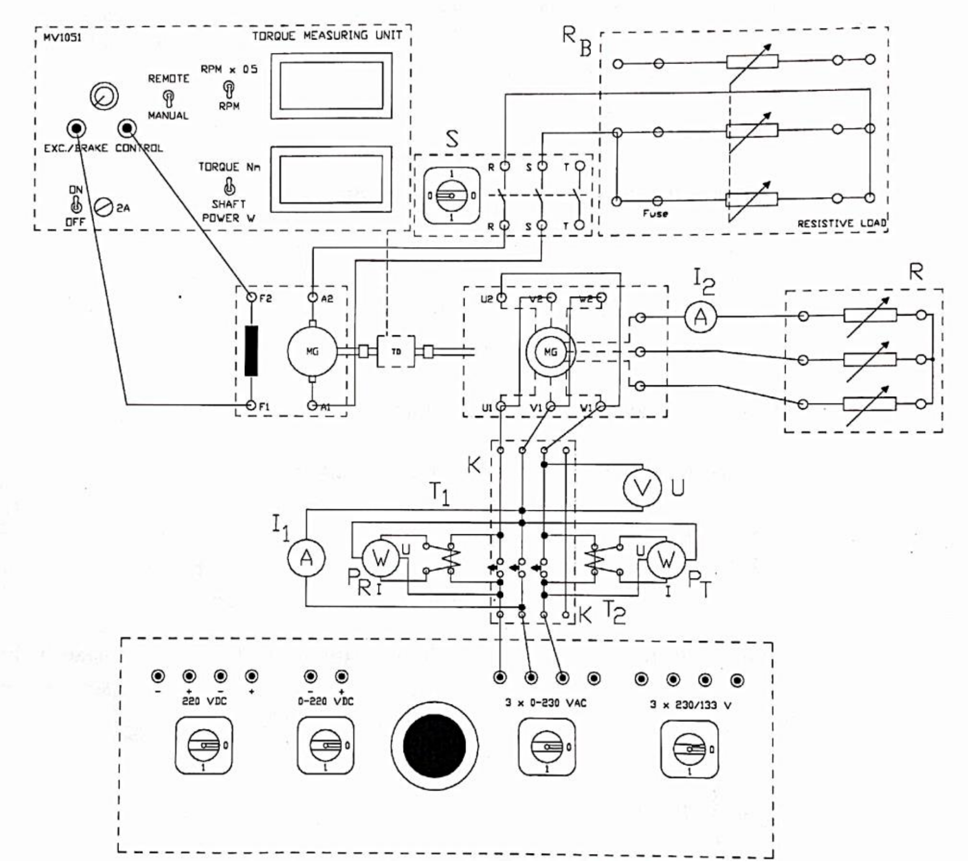
The induction motor efficiency is calculated using equation 2.11.

$$\eta = P_n/(P_n + P_0 + P_{cum} + P_{brush} + P_{stray}) \qquad (2.11)$$

2.2 METHODOLOGY

2.2.1 Connecting up

The braking machine is connected as a generator and the asynchronous motor in a delta circuit as shown in Figure 2.1.



Source: TERCO experimental manual, electrical machines with MV 1051 part 1.

Figure 2.1: Measure the efficiency for the slip-ring induction motor.

Where:

G = DC machine MV 1028 (alt. MV 1034)
T_D = Torque transducer and torque measuring unit MV 1051
M = Induction motor MV 1007
R_B = Load resistor MV 1100
R = Rotor starter MV 2636 (alt. MV 1013)
U = Voltmeter MV 1926
I_1 = Ammeter MV 1923
1_2 = Ammeter MV 1924
P_R, P_T = Wattmeter MV 1927
T_1, T_2 = Current transformer MV 1931
K = Terminal board with short-circuit buttons MV 1417
S = Switch MV 1500
F = Power supply MV 1300

2.2.2 No-load test

The sum of all losses are determined in no-load test. To ensure that the result is not influenced by losses in the DC machine, the asynchronous motor is separated from the braking machine during this test by gently pressing on the side.

The rotor starter is adjusted so that all resistance is connected to the rotor circuit as shown in figure 2.2. The variable AC voltage switch was turned on and the voltage was set at 230V. If the engine started slowly, the rotor starter was switched off.

The voltage U was set to 230 V and all deflections of the instruments were noted. The rotor starter was turned back to full resistance and the AC switch was also turned off.

2.2.3 Resistance measurement

In order to be able to calculate the losses, the resistance in the stator and rotor windings were measured. The stator termination is separated leaving the delta connection intact. The three resistances between U_1, V_1 and W_1 were measured with an ohmmeter. The rotor starter leading to the rotor is disconnected and the ohmmeter is then connected between two of the terminals. During the measurement, the rotor is turned slightly and the deflections of the instrument change are observed. This is due to the different resistances of the brushes; to avoid this, the housing is opened over the slip rings of the motor and the resistance is measured directly at the slip rings. The three resistances between the slip rings were also measured. The connection are shown in figure 2.3.

Figure 2.2: No-load measurement.

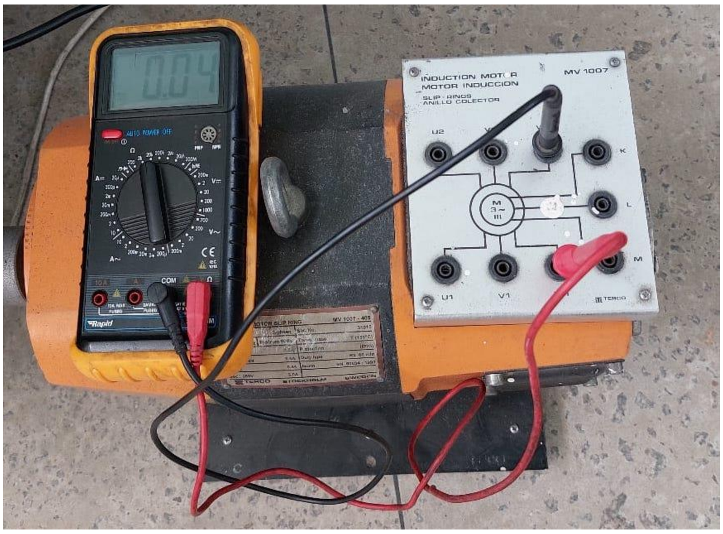


Figure 2.3: Resistance measurement

2.2.4 Direct measurement

The asynchronous motor is connected to the DC machine and the connection is checked as shown in Figure 2.1. The rotor starter is adjusted so that full resistance is connected to the rotor circuit. The variable AC voltage switch is turned on and set to 230V. When the engine is started, the rotor starter is slowly turned off.

With the switch S in figure 2.1 off, the excitation potentiometer of the torque measuring unit is set to minimum excitation current and the main switch is switched on. The voltage U is set to 230 V and kept constant during the measurement. The asynchronous motor is loaded in steps of 2 Nm to 7.5 Nm. This is done by varying the excitation current of the braking DC machine and by adjusting the load resistance RB. For each step, the following parameters were noted. They are U, I_1, P_R, P_T, I_2, T and n (for 1_2 write down the mean). In addition, the load is reduced to a minimum again.

2.2.5 Starting current

With this motor, the starting current is so high that it cannot be measured directly. Instead, the current is measured at slightly lower voltages and the inrush current is determined by extrapolating a curve through the measurement points. To avoid irregularities caused by stator and rotor slots, the rotor should be turned very slowly by hand during the measurement.

The variable AC voltage is set to 0 and the rotor starter to 0 resistance. The AC switch is turned and carefully increased so that the stator current increases in l A increments up to the rated current. For each step, U and I_1 are noted. Then the AC voltage is regulated down to zero.

The rotor starter is adjusted so that its entire resistance is connected to the rotor circuit. The AC voltage is carefully increased so that the stator current increases in steps of l A up to the rated current. For each step, U and I_1 were noted, after which the AC switch is turned off. The connection is shown in figure 2.1.

3. RESULT AND DISCUSSION

The governing equations in Section 2.1 are used to determine the performance of a slip ring induction motors.

3.1 No load test result.

Table 1 shows the no load measurement result. However, we need to determine the components of this machine from the no-load test.

Table 1: No load test

Measured values				
U (V)	I_1 (A)	P_R (W)	P_T (W)	I_2 (A)
230	4.58	-350	650	0.2

No load test values can be calculated using the following equation:

$$P_{om} = P_R + P_T = 650 - 350 = 300 \text{ W}$$

$$\tan\varphi = \sqrt{3}(P_T - P_R)/(P_T + P_R). = \sqrt{3}\,((650 + 350)/(650 - 350))$$

$$= \sqrt{3}\,[(1000)/300] = 5.77$$

$$\varphi = \tan^{-1}(5.77) = 80.168^0$$

$$\cos\varphi = 0.171$$

$$I_{2\,rms} = I_2/\sqrt{2} \qquad \text{where } I_2 = 0.2 \text{ A}$$

$$= 0.1414 \text{ A}$$

3.2 Resistance Measurement Result

The measurement result is shown in Table 2.

Table 2: Resistance measurements

Measured Values			
Resistance	R_1 (Ω)	R_2 (Ω)	R_3(Ω)
Stator	2	2	2
Rotor	4.8	4.8	4.8

From equation 2.4, R_{mean} for Stator = 2 Ω, and R_{mean} for Rotor 4.8 Ω

The resistance losses in stator and rotor for the measurement is determined from equation 2.5.

Thus, resistance loss in stator, where R_u = 2 ohm and I_1 = 4.58 A

$$P_{cuo1} = \left(\frac{3}{2}\right) \times R_u \cdot I^2 = \frac{3}{2} \times 2 \times 4.58^2 = 62.93 \text{ W}$$

For resistance loss in rotor, where Ru = 4.8 ohm and I_2 = 0.2 A

$$P_{cuo2} = \left(\frac{3}{2}\right) \times R_u \cdot I^2 = \frac{3}{2} \times 4.8 \times 0.2^2 = 0.29 \text{ W}$$

$$\text{Therefore,}\ P_{cuo} = P_{cuo1} + P_{cuo2} = 62.93 + 0.29 = 63.22 \text{ W}$$

3.3 No-load losses

Thus, the actual no-load losses can be calculated using $P_0 = P_{0m} - P_{Cu0}$ Recall equation 2.6

Where P_{om} = 300 W and P_{cuo} = 63.22 W

Therefore, P_0 = 236.78 W

3.4 Resistance and resistance losses calculation

Equation 2.7 is used to calculate the resistances at 75^0C for the stator and rotor.

For the stator: Rt=2 Ω at t=20^0C, R_{75} is calculated as 2.41 Ω

For the rotor: Rt=4.8 Ω at t=20^0C, , R_{75} is calculated as 5.79 Ω

The resistance losses in stator and rotor at rated current P_{cum} are calculated using equation 2.8.

For the Stator: R_{u75} = 2.41 Ω and I = 4.58 A, then stator P_{cum} = 75.86 W

For the rotor: R_{u75} = 5.79 Ω and I = 0.2 A, then then rotor P_{cum} = 0.35 W

Therefore, the total resistance losses, P_{cum} = 76.21 W

3.5 Brush resistance losses

Equation 2.9 is used to determine the brush resistance losses, P_{brush} where 0.3 is the voltage drop in brush and I_{2n} is the rotor current at rated load = 4.58 A.

Therefore P_{brush} = 4.12 W

3.6 Determination of stray losses

The stray losses in iron and conductors together as $P_{stray\ loss}$ is calculated using equation 2.10. Where P_n = output power of the machine at torque 7.5 Nm from direct measurement = 1400 W as shown in Table 3.

Table 3: Direct Measurements

Measured Values					
I_1 (A)	P_R (W)	P_T (W)	I_{2mean} (A)	T (nm)	n (rpm)
5.7	150	1400	1	7.5	1504

Thus, $P_{stray\ loss} = 0.01\times 1400 = 14$ W

3.7 Efficiency computation of slip ring induction machine

$$\eta = P_n/(P_n + P_0 + P_{cum} + P_{brush} + P_{stray}) \qquad \text{Recall equation 2.11}$$

$$\eta = 1400/(1400 + 236.78 + 76.21 + 4.12 + 14)$$

$$= 1400/1701.11 = \ = 82\ \%$$

The calculated efficiency is based on the assumption of leakage etc. and therefore may not be as accurate and reliable as the direct method result.

3.8 Starting current

Because the starting current is so high, the stator current is increased in 1A increments up to the machine's rated current of 5A. At 1 A, the measured voltage is 2.17% without rotor resistance and 20.87% with rotor resistance. However, starting currents of 2 A, 3 A, 4 A and 5 A result in 6.17%, 10.00%, 13.91% and 17.31%of the voltage measured without resistance respectively. In contrast, there are voltage recordings of 57.39%, 80.43%, 93.48% and 100% with rotor resistances at corresponding stator currents of 2 A, 3 A, 4 A and 5 A, respectively.

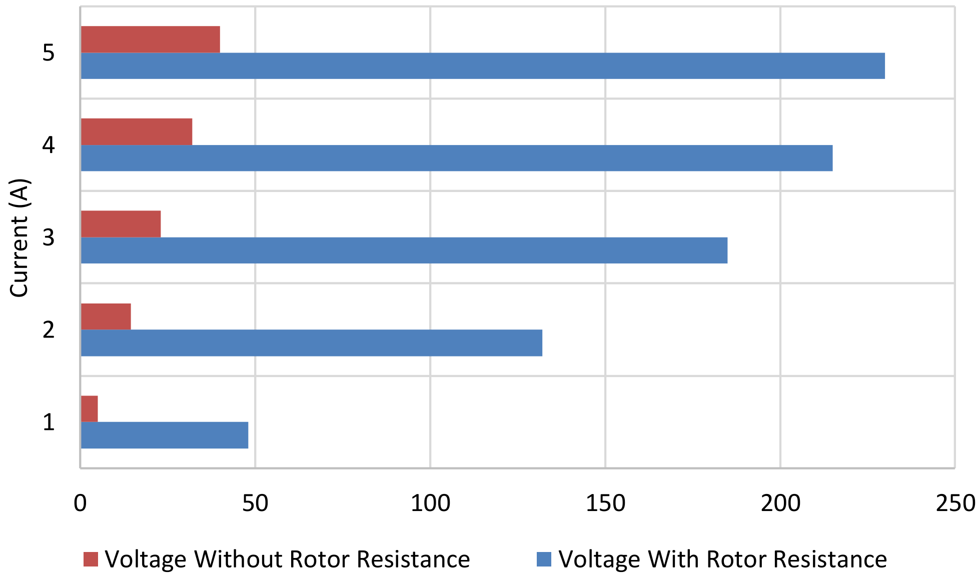


Figure 2.4: Starting current

4. CONCLUSION

This paper is based on the experimental study of performance determination of slip ring induction motors using TERCO equipment. The determination is based on the total loss method, which provides for a separate assessment of the individual losses. The losses in an asynchronous motor consist of load current independent losses, such as core losses, friction losses in bearings, ventilation losses, friction losses in brushes, and load current dependent losses, which include resistive losses in the primary winding, resistance losses in the secondary winding, brush resistance losses, stray losses in iron parts and stray losses in conductors. The resistance losses in the stator and rotor are found to be 63.22 W, while the actual no-load losses of the slip ring induction motor are found to be 236.78 W. Other resistance calculations that emerge from the measurements include the resistances at 75^{0}Celsius, which are calculated as 8.2 Ω. Also, the losses at 750 °C are calculated to be 76.21 W. Thus, the brush resistance losses are determined to be 4.12 W when calculating the stray losses as 14 W. The slip ring induction motor efficiency is calculated as 82% based on the total value. However, the efficiency calculated on the summation method depends on assumptions and may not prove to be reliable and accurate. In addition, the starting current measurements are taken with and without rotor resistances at lower voltages. Slip ring induction shows better starting performance when connected to rotor resistance.

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