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Performance analysis of three-phase induction motor for railway propulsion system

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ABSTRACT

A three-phase induction motor absorbs the most electric power among other electrical loads. Therefore, three-phase induction motors are the primary electric motors used in industrial applications thanks to their simple construction and easy operation, as well as low cost and low maintenance costs. Efficiency is a critical parameter that characterizes an induction motor as a traction motor. The traction motor is defined as the engine's effectiveness in converting electrical power at its input into mechanical energy by rotating torque on its axis. One way to analyze the efficiency is to use test data obtained from laboratory tests in case-loaded and no-load tests. Calculations using several formulas on the efficiency of an induction motor as a traction motor produce the same result, namely the efficiency of 98.6% by applying variable frequency drive (VFD). The result of laboratory tests and their analysis can be used as a reference for designing three-phase induction motors for railway traction motors, especially traction motors for high-speed trains.

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1. INTRODUCTION

Currently, the global world is promoting the use of electric vehicles (EV), both in the form of electric cars and electric trains, to reduce high levels of pollution in the environment [1]–[3], where the main component is an electric motor. It is called an electric motor because the power source is to drive the induction motor (IM) using electricity. IM as traction motors have other advantages such as regenerative braking ability, near-unity power factor, nearly perfect sinusoidal current, good adhesion, high rotational speed rate, and high efficiency [4]. One type of IM that is widely used is the linear induction motor (LIM). The LIM was initially considered impractical because it was challenging to make the air gap between the stator and rotor windings as small as possible [5]. Besides that, another type of induction motor, the rotary induction motor (RIM), has a lower power factor than the typical three-phase induction motor [6]. Another type of induction motor is a three-phase induction motor (TPIM). At the same time, TPIM absorbs the most electric power among other electrical loads [7]. The TPIM is the main electric motor used in industrial applications thanks to its simple construction, easy operation, low cost, and low maintenance costs [8], [9].

Nowadays, TPIM used in the type of electric train uses a propulsion system called the electric multiple unit (EMU). In Indonesia, there are several types of EMU trains, including its use in the light rail transit (LRT) and electric rail trains (KRL) that have been used in the Greater Jakarta area (Jakarta-Bogor-

Depok-Tangerang-Bekasi) [10]–[12]. Apart from these types of electric trains, there are trains that are also used by many people, namely KRDE or diesel-electric train, the technological innovation at PT. INKA uses a three-phase induction motor as its traction motor [12]. In addition, the Jakarta-Bandung high-speed train also uses an EMU drive and is currently being built with a maximum operating speed of 350 km/h [13].

To get the benefits of TPIM used in EMU trains, it is crucial to evaluate the performance and characteristics of the TPIM constantly. Using computational simulation and laboratory tests, evaluate TPIM as a traction motor under several operating conditions. Kumar *et al.* [14] developed induction motor models using the Thevenin equivalent circuit to determine the maximum electromagnetic torque and the slip that occurs. Dynamic engine models in all three frames of reference are then analyzed. The results obtained from the steady-state model are validated with the dynamic model. Lee *et al.* [15] researched injecting the harmonics of the inverter switching frequency through the finite element analysis (FEM) model analysis at the time of design and verification of the method with the test of the produced model. The aim is to minimize the difference between the analysis results and experimentation when analyzing the traction motor. The efficiency value depends on the number of losses, both fixed and variable losses, which are highly related to the voltage and current of each phase [16]. Induction motor laboratory test using an EMU train to describe when the train is operating [17]. Laboratory tests on three-phase induction motors to control motor speed, namely the direction of rotation, and also assess motor performance with parameters of current, power factor, speed, torque, and power [18], [19]. An induction motor test method that only requires no-load testing to extract the parameters of the induction machine [20]. The proposed method is based on a modification of the calculation of the third impedance of the IEEE 112 standard. This test with an improved leakage reactance calculation using the machine's no-load startup power and current at the lowest voltage test point.

This paper analyzes the performance of induction motors used as traction motors on EMU trains. This method is proposed to provide a simple way to calculate and analyze efficiency as one of the main parameters of induction motors used as rail traction motors. The analysis used test data from the minimalist test equipment regarding measuring instruments and loading equipment. Performance analysis in the form of efficiency is carried out using test data from both no-load and load tests. As a result, some tests cannot be performed, including tests using direct current (DC) power sources and clogged rotor tests.

2. METHOD

2.1. Performance of traction motor

Three phases induction motor is an electric motor that converts the electrical energy of three-phase alternating current into mechanical energy in the form of torque and rotation. As explained earlier, three-phase squirrel cage induction motors were widely used as traction motors. One of the main parameters of using an induction motor as a traction motor is its efficiency. Efficiency is defined as the ability of an induction motor to convert the electrical energy input into mechanical energy in the form of torque and rotation on its axis (or output). The formula is shown in (1).

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{mechanical}}{P_{electrical}} \quad (1)$$

Where is efficiency in %, P_{out} is output in kW, P_{int} is input in kW. The calculation of the induction motor's efficiency using the formula given in (1) can be carried out by directly measuring the input energy given and the output torque under load according to the capacity rating.

In addition to these direct measurements, indirect efficiency measurements can also be carried out by measuring the power loss on the motor P_{loss}. This method is known as segregation or summation of losses. Furthermore, the efficiency is determined from the total loss because the output power equals the input power in electrical energy minus the power loss P_{loss} [21].

$$P_{out} = P_{in} - P_{loss} \quad (2)$$

The power loss on the motor (P_{loss}) is given by (3).

$$P_{loss} = P_{statloss} + P_{rotloss} + P_{irloss} \quad (3)$$

Where losses in the stator define by $P_{statloss}$, $P_{rotloss}$ are losses in the rotor, and P_{irloss} are losses in the induction motor [22]. Based in (2), the efficiency formula, which was shown in in (1) can be rewritten as (4).

$$\eta = \frac{P_{in} - P_{loss}}{P_{in}} = \frac{P_{electrical} - P_{loss}}{P_{electrical}} \quad (4)$$

Based (4), the efficiency is measured by taking into account the input power of the traction motor, which was in the form of a three-phase electricity current, and the losses occurred. Since the efficiency is calculated based on the input power in three-phase power, the balance between the phases greatly determines the calculation results [6], [23]. From the output point of view, where mechanical power is in the form of torque and rotation-then by substituting in (4) into in (1), the induction motor efficiency formula in (1) can also be written as in (5).

$$\eta = \frac{P_{mechanical}}{P_{electrical}} = \frac{P_{mechanical}}{P_{mechanical} + \Sigma\ losses} \quad (5)$$

In (5) is the opposite of in (4), where efficiency is calculated based on the output power generated by the traction motor, namely mechanical power in the form of torque and losses that occurred. When the induction motor as a traction motor is run without load, the motor will draw power from the system to overcome the losses in the IM. If the load is put on the motor's axis, the motor will remove more power from the system to overcome the given load. The losses only increase slightly as the load increases; thus, efficiency will increase accordingly. Efficiency will continue to increase with increasing load as long as the output power increases faster than the input power until the maximum load condition.

2.2. Calculation of traction motor's efficiency

The efficiency of a small-sized induction motor can be calculated using a direct load test by giving it a load and then measuring its input and output power. Next, the efficiency is calculated using in (1). However, powerful induction motors, such as those used as train traction motors with specifications in Table 1, would require special tests [4], [24].

Table 1. Technical specification of traction motor

Type	Three-phase induction motor
Power output	180 kW
Voltage input	1000 VAC–1200 VAC
Speed	2000–2200 rpm
Current	122 A
Torque	848 Nm
Frequency	80.73 Hz

Such a particular test consists of 2 kinds: no load test and blocked rotor test. Both tests are needed to determine the losses incurred (P_{loss}), consisting of fixed and variable losses. From the two tests, a replacement circuit for an induction motor was formed, which is used to analyze various parameters of the induction motor. Due to several constraints, the blocked rotor test was not carried out and was replaced with a loaded test. Before explaining further, the losses that occur in the induction motor as a traction motor, it is necessary first to describe the power flow in the induction motor operation, as shown in Figure 1.

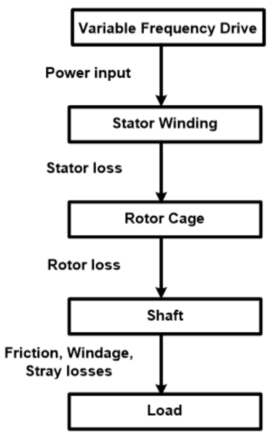

Figure 1. Energy flow on induction motor

It can be seen in Figure 1 that when a balanced three-phase alternating current is applied to the stator winding, a rotating magnetic field (RMF) is generated by the stator winding. The RMF rotates around the stator at the synchronous speed given in (6).

$$N_s = \frac{120\, f_s}{P} \tag{6}$$

N_s is the stator's frequency, p is the pole, and f_s is the frequency of the stator. The rotating magnetic field generated by the three-phase stator current passes through the air gap and cuts the rotor conductors, which are not yet stationary. Not all of the electrical power input to the stator is converted into a rotating magnetic field. Some are lost to heat, and others are called stator losses.

The rotor is a cage with both ends shorted, so current flows in the rotor conductors. Meanwhile, the current flowing in the rotor conductor is in the magnetic field generated by the stator winding. Thus, the rotor conductor experiences a mechanical force. Most of the mechanical forces on all rotor conductors produce a torque that moves the rotor in the same direction as the rotating magnetic field. Furthermore, the central component of the rotor is the rotor shaft, which is also the main component of the electric motor. The rotor shaft generates mechanical energy transmitted to the connected load.

Core losses are losses that occur in the stator core and rotor core. These losses are also called iron losses because the stator core and rotor core are made of high-quality steel. Iron losses consist of eddy current losses and hysteresis losses. The iron losses depend on frequency, while the stator frequency is the input supply frequency; thus, the stator iron losses become dominant. Meanwhile, the iron losses in the rotor are minimal because the rotor frequency is so small that it can be ignored. The frequency has resulted from multiplying the slip and the supply frequency because the stator frequency equals the supply frequency.

$$f_r = s \cdot f_s \tag{7}$$

Where f_r is rotor frequency, s is slip, and f_s is stator frequency. The slip value (s) is minimal in the range of 5% when the motor is run at full load: other fixed losses, namely mechanical losses, including friction losses in bearings. Friction losses change with speed changes (rotation of the rotor). Still, the differences in these losses are so minor at a specific frequency that friction losses can be considered part of constant losses.

Variable losses of induction motors are often also called copper losses, which are directly proportional to the quadratic stator current in the stator winding and directly proportional to the rotor current. Since the amount of the stator current and rotor current correspond to changes in load, the copper losses vary with changes in load. The amount of copper losses in the stator winding is shown in (8).

$$P_{stat-loss} = I_{stat}^2 \cdot R_{stat} \tag{8}$$

Where $P_{stat\text{-}loss}$ is copper stator losses, I_{stat} is current in the stator winding that change according to load, R_{stat} is resistance in the stator winding, copper losses in the rotor are shown in (9):

$$P_{rot-loss} = I_{rot}^2 \cdot R_{rot} \tag{9}$$

where $P_{rot\text{-}loss}$ is rotor copper loses, I_{rot} is rotor current that changes according to load, R_{rot} is rotor resistance.

3. RESULTS AND DISCUSSION

All the processes described are energy conversion processes, and in each process, energy is not utilized (wasted), called losses. Data or information obtained from the no-load test were, among others, no-load losses such as core losses, friction losses, wind losses, and no-load rotor copper losses. Since the no-load rotor copper losses are minimal, they can be neglected. The proposed method is to configure and test the experimental model using a motor dynamometer. The facilities used to test a 3-phase cage rotor induction motor as a rail traction motor are shown in Figure 2. The source of electricity is taken from the PLN 380 Vac electricity network, which is connected to a step-up transformer to 600 Vac and 1200 Vac, which is then used as a power source for traction motors. Traction motor testing uses an AC–AC converter to change the desired frequency.

3.1. Fixed losses

The no-load test on the induction motor with the specifications in Table 1 resulted in input power, output power, and losses at a specific speed, as shown in Figure 3. Motor loss (P_{loss}) in Figure 3 is called fixed losses, or losses considered constant during an induction motor's normal working range at a specific frequency. They consist of iron or core, mechanical, and brush friction losses.

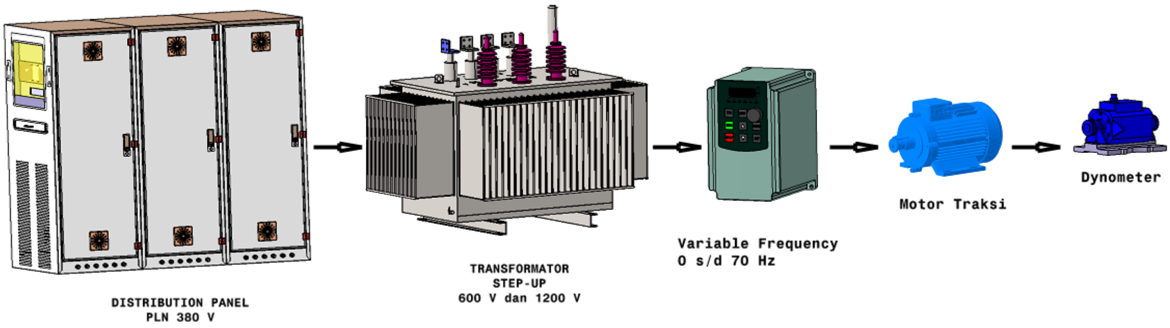

Figure 2. The facilities for 3-phase induction motor testing

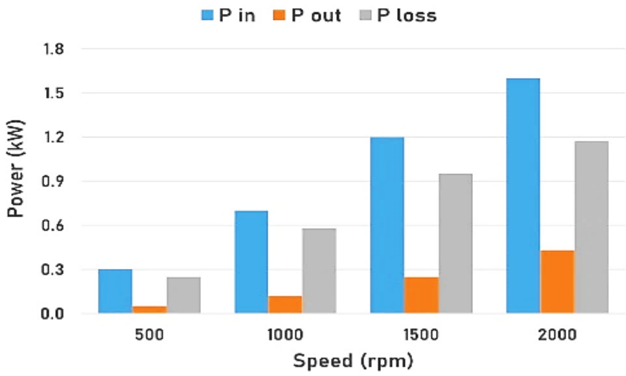

Figure 3. No load tests

Other data and information needed are variable losses. Variable losses are generally measured by blocked rotor testing. The test is identical to the short circuit test in the transformation test. A test on an induction motor with a retained rotor is carried out to determine the characteristics of an induction motor when it is fully loaded. This test will show the short circuit current at standard voltage, power factor in the short circuit, total leakage reactance, and motor starting torque. However, the test was carried out at low voltage because the standard voltage will allow high current through the stator winding-this will be high enough to heat the winding and damage it.

In blocked rotor testing of induction motors, the voltage applied to the stator terminals must be low because standard voltages can damage the stator windings. The execution of the test is that a low voltage is used so that the rotor does not rotate, its speed becomes zero, and full load current passes through the stator winding. Based on this, the blocked rotor test was not carried out and was replaced with a loaded rotor test. However, it isn't easy to give it a load according to its capacity for an induction motor with a large capacity, such as an induction motor for applying a train propulsion system. In addition, the power loss will be significant with a direct load test.

3.2. Variable loss at a specific frequency

In the test under load conditions described above on the induction motor with Table 1 specification, the applied load only varies from 10% to 40% of the motor capacity. Induction motor variable losses when the motor is loaded include copper losses in the field winding. These losses change according to changes in the load on the motor, it increases when the load increases and vice versa. Therefore, these losses are not constant over a long period and are known as variable losses. Test results on induction motor with Table 1 specification showed losses variable graph in Figure 4.

Figure 4 shows that variable losses at a specific frequency will change according to changes in load, based on the formula shown in (6) and (7). Furthermore, a total loss is obtained using the extrapolation principle on the induction motor test results data with the specifications in Table 1. The losses from the start of the non-loaded operation to the fully-loaded operation are shown in Figure 5.

The bandwidth of the torque hysteresis controller mainly affects the switching frequency. The initial bandwidth of the torque hysteresis controller must be adjusted according to the worst-case conditions. The worst case is at low or high-speed operation, where the reverse voltage vector must not be selected in steady-state operation, as mentioned in the previous section. Another worst-case situation is ensuring the switching frequency does not exceed the limit set by the thermal limiting value of the power switching device (like IGBT in this case) [24], [25].

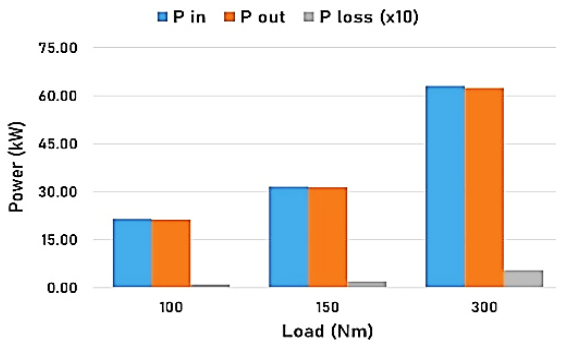

Figure 4. Variable losses according to load changes

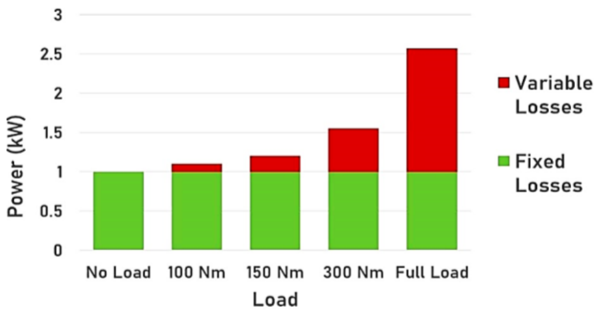

Figure 5. Total losses according to load changes

3.3. Motor efficiency

Based on the combination of the two test results, it is known that efficiency rises sharply from no load to full load state, losses start faster, and efficiency becomes sloping, as shown in Figure 6. Figure 6 shows that the efficiency moves sharply from the load to the given minimum load, about 21% of the motor capacity. Furthermore, the efficiency moves depreciation towards 98.6% until it is at full load. The loading is only up to 300 Nm, equivalent to 35% of the motor capacity. Furthermore, linear extrapolation is used to calculate the efficiency from 21% load to full load. An efficiency of 98.6% is obtained either from a calculation using in (1), (4), or (5). The losses of 1.3% consist of fixed losses of 0.8% and variable losses of about 0.5%. Several studies have also shown that an induction motor whose electrical energy input is supplied from electronic equipment in the form of a variable frequency drive (VFD) or a variable voltage and variable frequency (VVVF) inverter will provide high efficiency above 95% [26], [27].

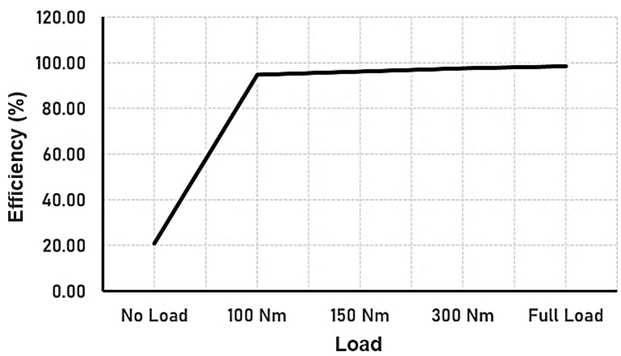

Figure 6. Efficiency from no load to full load

4. CONCLUSION

Induction motors used as traction motors have advantages such as having regenerative braking ability, easy maintenance and relatively short maintenance time, simple construction and easy operation, and low operating and maintenance costs. The no-load and loaded test found that the induction motor used as a train traction motor has small fixed losses, about 0.1% of the motor capacity. The variable losses vary according to changes in load. By giving the load only 10% to 40% of the motor capacity, the efficiency of the induction motor used as a traction motor is 98.6%. This high efficiency is possible using electronic equipment as a variable frequency drive (VFD) inverter.

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