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Impact of Ball Bearing Damage Variations on the Efficiency of Squirrel Cage 3-Phase Induction Motors

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Abstrak—Penelitian ini bertujuan untuk mengetahui diagnosa awal adanya kerusakan pada motor induksi 3 fasa. Bantalan bola merupakan salah satu komponen penting pada sepeda motor ini yang berperan dalam menopang beban dan membuat putaran menjadi lancar. Namun seperti semua komponen mekanik, ball bearing pada motor induksi 3 fasa juga rentan terhadap kegagalan kinerja motor bahkan dapat menyebabkan kerusakan pada motor secara keseluruhan. Ada beberapa cara untuk mendeteksi beberapa gangguan pada motor induksi, yaitu melalui analisis kecepatan, fluktuasi arus, dan kenaikan suhu motor saat beroperasi. Berdasarkan data hasil pengukuran selama 14 hari, nilai arus rata-rata pada kondisi bantalan normal sebesar 1,36 A, sedangkan pada kondisi bantalan rusak nilai arus rata-rata sebesar 1,55 A dan pada kondisi bantalan berkarat sebesar 1,52 A. Peningkatan arus tersebut disebabkan oleh karena rotor tidak berputar secara seimbang sehingga medan listrik pada stator berubah, hal ini menyebabkan peningkatan arus operasional dan temperatur motor.

Kata kunci : Efisiensi, Motor Induksi 3-Fasa, Kerusakan Bola Bearing

Abstract— *This research aims to determine the initial diagnosis of damage to a 3-phase induction motor. Ball bearings are one of the important components in this induction motor which play a role in supporting the load and allowing smooth rotation. However, like all mechanical components, ball bearings in 3-phase induction motors are also susceptible to failure in motor performance and can even cause damage to the motor as a whole. There are ways to detect several disturbances in induction motors, namely through speed analysis, current fluctuations, and increases in motor temperature when operating. Based on the results of measurement data for 14 days, the average current value in normal bearing conditions is 1.36 A, while in broken bearing conditions the average current value is 1.55 A and in rusty bearing conditions 1.52 A. The increase in current is due to because the rotor does not rotate in a balanced manner so that the electric field in the stator changes, this causes an increase in the motor's current and temperature.*

Keywords : *3-Phase Induction Motor*, *Ball Bearing Damage, Efficiency*

I. Introduction

Induction motors are an example of a type of electric motor that is commonly used in industry due to its simple construction and easy maintenance [1]. An induction motor in an electricity generation system is very necessary because the function of the induction motor is to act as a driver. An induction motor has several parts, one of which is a bearing, where the bearing works in the induction motor as the part that causes the motor to rotate. If a disturbance occurs due to a sudden change in load or overload, it will cause fatal damage to the bearing. Damage to motor parts is one of the causes of changes in efficiency so that the motor cannot function optimally.

Bearings have an important role in motor performance. Damage to motor bearings reaches 41-44%, this is the largest percentage of damage that occurs. Three other parts that experience a lot of damage to induction motors are the bearing, stator and rotor. The percentage of damage to motors includes damage to bearings 41%, stator 37%, rotor 10%, and other parts 12% [2]. Therefore, bearing damage can be categorized as the most common and major damage to induction motors.

Bearings are a part of a machine element whose main function is to maintain position by limiting the relative movement between two or more interconnected mechanical components so that they always move in the desired direction of motion [3]. Bearings function to reduce friction of rotating equipment on the shaft or axle and to support a shaft so that it can rotate without experiencing excessive

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friction. Bearings are mechanical components of machines that function to reduce friction between two moving machine components, support the rotating position of machine components, and facilitate rotation of the rotating shaft against fixed components.

The efficiency of a tool is a measurement of how maximally the tool is able to make changes from input to output. The decline in motor efficiency causes disruption to industrial performance. The decrease in efficiency greatly affects the condition of the induction motor, when the induction motor is damaged, the efficiency will decrease. Therefore, regular maintenance is required. Damage that is commonly found in induction motors is mechanical damage that occurs due to changes in load or overload, resulting in damage to the ball bearing. This impact causes a decrease in motor efficiency, resulting in less than ideal performance of the induction motor [4]. A decrease in efficiency can be considered as a sign of damage that has occurred. Therefore, the impact produced by bearing damage is not only on the current spectrum but is also characterized by decreased efficiency [5].

Based on the research that has been explained, this research will develop motor efficiency due to ball bearing damage through stator current. Damage to the bearing can result in a decrease in motor efficiency. This decrease in efficiency causes the induction motor to not work optimally. In this research, an analysis of the reduction in motor efficiency will be carried out by carrying out several experiments in the form of bearing damage construction, namely missing ball bearing damage 1, missing ball bearing damage 2 and scratched damage. Diagnosis is carried out to detect damage to the bearing, after which an efficiency analysis is carried out on the motor. From the results of the research, by knowing the efficiency, damage to the induction motor that occurs can be known so that more serious damage can be minimized.

II. LITERATURE REVIEW

A. *Related Research*

The efficiency and performance of bearings contribute effectively to the successful operation of rotating machinery. Hence, the selection of bearing material is of great importance to meet the expectations of the machine for better performance and successful running life of machines. Bearing materials should have capabilities that are a combination of properties such as fatigue strength, compatibility, cavitation, conformability, corrosion resistance, and erosion resistance.

A single material never completes all the requirements of good-bearing material. Hence, a combination of the above properties is necessary to meet all the requirements for successful operations and high-end performance of any type of bearing [6]. Bearings are the most critical element in machines as most of the wear occurs in bearing components and maximum failure of the system takes place due to faulty bearings. The bearing of good quality can increase the performance of machines and if it is defective, it can cause serious damages and failures [7]. Liu and Zhang [8] reviewed the different types of failure modes, failure mechanisms and provided useful references for engineers & researchers to understand material issues in bearing and also make them possible with their review to be more cost-effective and easy to use methods.

According to ISO 15243: 2004 [9], [10] The failure perspectives are divided into six categories of bearing failure types. Failure modes in large-scale bearings are classified into two groups named premature fatigue and failure of material [11]. The first group is premature fatigue based on mechanical failure. Premature fatigue consists of defects such as improper lubricant, improper mounting, improper maintenance, electrical erosion, and plastic deformation. The second group is the failure of materials induced by structures and components. These failures of materials are noticed as wear & cracks in bearings [12]. The different bearings have various kinds of failure because of their dissimilar operating conditions and design mechanisms. Due to the reasons i.e. operating conditions and design mechanisms, it becomes important to segregate failure in bearings based on their characteristics and data collection techniques.

B. *3-Phase Induction Motor*

Induction motors are alternating current machines that are widely used in companies operating in the industrial, commercial, aerospace and military sectors. A 3-phase induction motor has two main construction parts, the first is the stator, which is a stationary part, the second is the rotor, which is the moving/rotating part, so it has an air gap which is usually called the air gap. The main construction of an induction motor can be seen in Figure 1.

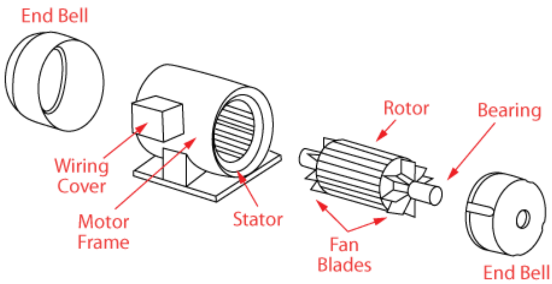

Figure 1. 3-Phase induction motor construction

The working principle is based on electric field coupling. The induction motor has a gap between the stator field and the rotor field. The source of the induced current is the relative difference between the rotor rotation and the stator rotating field. Induction motors do not use field coils.

An induction motor works based on electromagnetic induction from the stator coil to the rotor coil. If a three-phase voltage source is installed on the stator coil, a rotating field arises which rotates with synchronous speed (*Ns*), the magnitude of Ns is determined by the number of poles (*p*) and the stator frequency (*f*) which is formulated by [13]:

$$N_s = \frac{120 \times f}{p} \quad (1)$$

Where,

N_s = Synchronous speed (rpm)

f = Frequency (Hz)

p = Number of Poles

Because the rotor coil is a closed circuit, the electromotive force (EMF) will produce a current (*i*). The presence of current (*i*) in the magnetic field causes a force (*F*) on the rotor. If the initial couple produced by the Lorentz force (*F*) on the rotor is large enough to support the load, the rotor will rotate in the same direction as the stator rotating field.

As previously mentioned, the induced voltage arises due to the cutting of the rotor conductor rods by the rotating magnetic field of the stator. If the rotor speed is the same as the stator synchronous speed then the slip is zero, there is no flux cutting the rotor windings so that no voltage is induced in the rotor windings, so no current flows in the rotor windings, judging from the way it works, induction motors are also called asynchronous motors.

The greater the number of poles will result in the smaller the speed of the stator rotating field and vice versa. The speed at which this rotating field rotates is called synchronous speed. The amount of synchronization is as follows [14]:

$$\omega = \frac{N_s \times 2\pi}{60} \quad (2)$$

Where,

ω = Angular velocity (rad/s)

N_s = Synchronous speed (rpm)

Induction motor efficiency is defined as a measure of the effectiveness of the induction motor in converting electrical energy into mechanical energy which is expressed as a ratio or ratio of output power to input power. The NEMA definition of energy efficiency is that efficiency is the comparison or ratio of useful output power to total input power and is usually expressed in percent. Also often expressed as a ratio of output plus losses. The efficiency of the induction motor (η) is [15]:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad (3)$$

C. Ball Bearing Damage

Bearing damage is usually caused by several problems, for example overload, excessive heat, incorrect bearing installation and errors due to lubrication. The effects of bearing damage can cause vibrations, noise and excessive temperatures in the induction motor. Damage to the bearing can cause the induction motor to experience radial movement. This causes the flux density in the air gap to become asymmetrical and affects the inductance in the stator so that the stator current of the induction motor contains harmonics with a damage frequency that can be predicted using equation (3) [16].

$$F_P = |f_s \pm k.f_v| \quad (4)$$

III. METHODS

In this research, several methods will be used to detect ball bearing failure in 3 phase induction motors. There are several equipment needed for this research, such as ammeters, tachometers, thermometers and other equipment that is needed.

A. Stator Current Measurement

The electrical measuring instrument whose function is to measure the value of electric current in amperes. The unit used in this research is the ampere meter/clamp meter, which is specifically intended to measure alternating current (AC).

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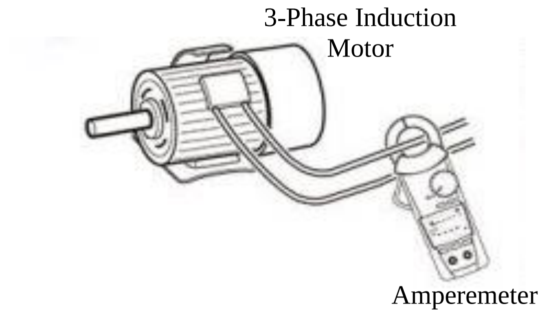

Figure 2. Measurement of the stator current value

B. *Temperature Measurement*

In this research, to identify motor damage, temperature observations were also carried out. The results showed that the thermometer was able to measure the temperature of the motor body which was produced from samples of motor with normal conditions and damaged bearing function. The resulting data was in accordance with the motor condition reference on the motor nameplate.

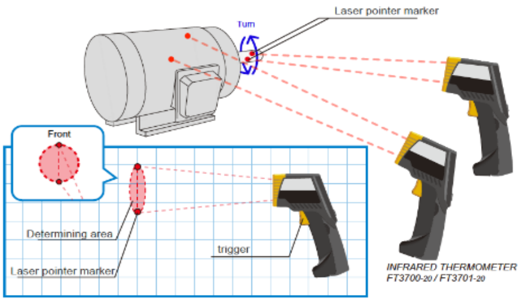

Figure 3. Hotspot temperature measurement

Insulation class on motor is a class division for motor resistance at certain temperatures. The NEMA (The National Electrical Manufacture Association) standard divides Insulation Class into 4, namely A, B, F and H. Table 1 and Table 2 explain the criteria for increasing temperature and hotspot margins.

Table 1. Rise Temperature Classification [17]

Thermal Class Rating	**Maximal Temperature**
Class A	60 [^{0}C]
Class B	80 [^{0}C]
Class F	105 [^{0}C]
Class H	125 [^{0}C]

Table 2. Hostspot Temperature Classification [18]

Thermal Class Rating	**Maximal Temperature**
Class A	105 [^{0}C]
Class B	130 [^{0}C]
Class F	155 [^{0}C]
Class H	180 [^{0}C]

C. *Bearing Reconstruction*

The reconstruction of the bearing condition was deliberately made flawed by breaking the track for the first condition. For the second condition, the bearing is rusted by soaking it in acidic water for several weeks. The variation in damage is intended so that the data produced is different, even though in reality in the field bearing damage of an undetermined magnitude occurs. Meanwhile, for the rolling elements, defects occurred in the balls and cages. The use of the same load is carried out so that the measurement value is the same for each damage so that analysis can be carried out using predetermined variables and minimizing the equipment testing error factor.

(a) (b)

Figure 4. Rekonstruksi Bearing (a) Rusty Bearing; (b) Broken Bearing

Table 3. Performance Specifications of Induction Motor

Power	1,1 [kW]
Frequency	50 [Hz]
Voltage	380 [Volt]
Class Insulation	F
Current	1.8 [Ampere]
Maximum Rotation	1500 [rpm]
Cos φ	0.85
Efficiency	85%

IV. RESULT DAN ANALYSIS

A. *Analysis of Hotspot Temperature*

The results of the measurement test data for 14 days will be added to the determination based on the NEMA (National Electrical Manufacture Association) standard which gives a standard room temperature value of 40°C. From the observations that have been made, the results are that the stator temperature for normal bearing conditions is 77,1°C, the temperature for broken bearings is 92,6°C, the temperature for rusty bearings is 88,2°C. This value is still below the standard of class F insulation value with a maximum temperature value of 105°C.

Table 4. Hostspot Temperature of Multiple Bearing Failures

	Hotspot Temperature (^{0}C)		
Day	**Normal Bearing**	**Broken Bearing**	**Rusty Bearing**
1	36,1 °C	50,1 °C	48,4 °C
2	36,5 °C	51,2 °C	49,1 °C
3	36,8 °C	52,6 °C	48,5 °C
4	36,3 °C	50,3 °C	48,8 °C
5	36,9 °C	49,9 °C	46,7 °C
6	37,1 °C	54,5 °C	47,9 °C
7	37,9 °C	55,1 °C	48,7 °C
8	36,9 °C	54,7 °C	47,4 °C
9	37,8 °C	53,2 °C	48,2 °C
10	36,6 °C	53,9 °C	47,7 °C
11	37,3 °C	52,9 °C	46,9 °C
12	38,6 °C	50,9 °C	48,7 °C
13	36,4 °C	52,3 °C	49,3 °C
14	37,6 °C	54,8 °C	48,6 °C

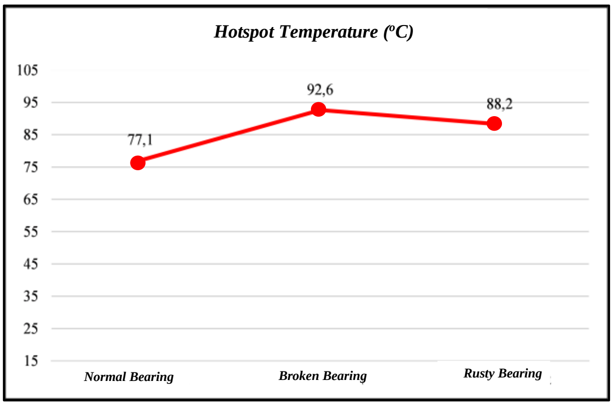

Figure 5. Hotspot temperature of 3-Phase Induction Motor

Based on Figure 5, when a ball bearing is detected to be damaged, the average temperature will increase by 19,9% from the maximum temperature of class F insulation, the maximum resistance of class F insulation based on NEMA is 105°C.

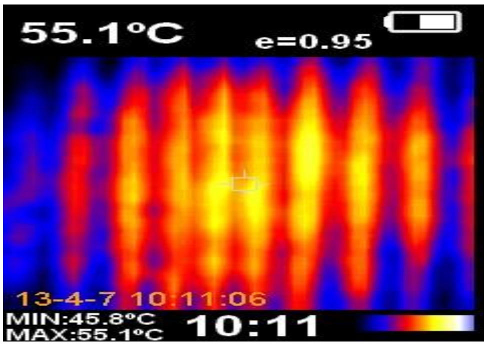

Figure 7. Hotspot temperature measurement results in broken bearing conditions

From Figure 7 you can see the results of measuring the hotspot temperature using thermo vision, it can be seen that the measured hotspot temperature is 55,1°C. If combined with room temperature with a value of 40^{0}C, the total temperature is 95,1^{0}C. This value corresponds to the maximum value for class F insulation.

B. *Analysis of Performance Motor*

The results of the test data for measuring the rotational speed of the induction motor using a tachometer for 14 days, the average speed in normal bearing conditions was 1482,1 rpm, in broken bearing conditions the average was 1432,1 rpm and in rusty bearing conditions 1437,3 rpm. When damage occurs, the rotation of the 3-phase induction motor will decrease. So it is necessary to check regularly before the winding catches fire which causes interference with other equipment that uses an induction motor.

Table 5. Rotation Speed of Rotor

	Rotor Rotation Speed (rpm)		
Day	**Normal Bearing**	**Broken Bearing**	**Rusty Bearing**
1	1483,4	1429,8	1439,6
2	1480,2	1431,5	1437,8
3	1479,8	1430,4	1440,2
4	1484,2	1431,6	1434,2
5	1480,8	1430,8	1435,8
6	1486,1	1429,6	1439,2
7	1483,2	1432,8	1438.4
8	1481,7	1432,9	1435,8
9	1486,9	1435,8	1435,7
10	1482,8	1434,4	1434,6
11	1480,7	1432,1	1435,3
12	1482,5	1430,5	1438,7
13	1480,9	1432,3	1437,4
14	1479,9	1434,1	1439,8

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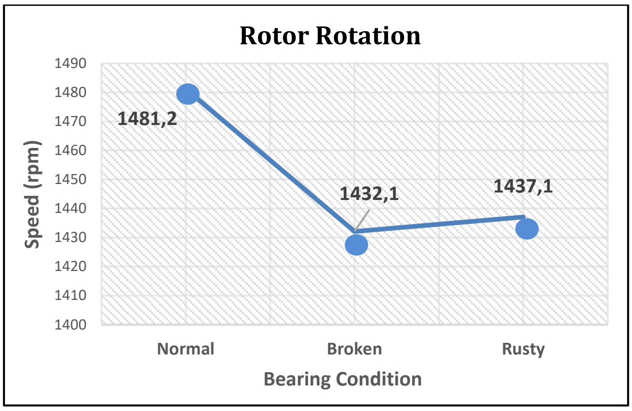

Figure 5. Rotor rotation of 3-Phase Induction Motor

Based on Figure 5, when the ball bearing is normal the resulting speed is 98,68% of the nameplate and when damage to the ball bearing is detected the speed will decrease by 5% to 10% of the speed.

Table 6. Stator Current of Multiple Bearing Failures

Day	Stator Current (Ampere) Normal Bearing	Broken Bearing	Rusty Bearing
1	1,35	1,56	1,53
2	1,36	1,59	1,5
3	1,38	1,57	1,48
4	1,36	1,5	1,54
5	1,38	1,58	1,53
6	1,34	1,6	1,5
7	1,36	1,54	1,51
8	1,37	1,55	1,54
9	1,35	1,54	1,55
10	1,34	1,49	1,52
11	1,37	1,5	1,5
12	1,35	1,57	1,54
13	1,39	1,59	1,51
14	1,35	1,54	1,55

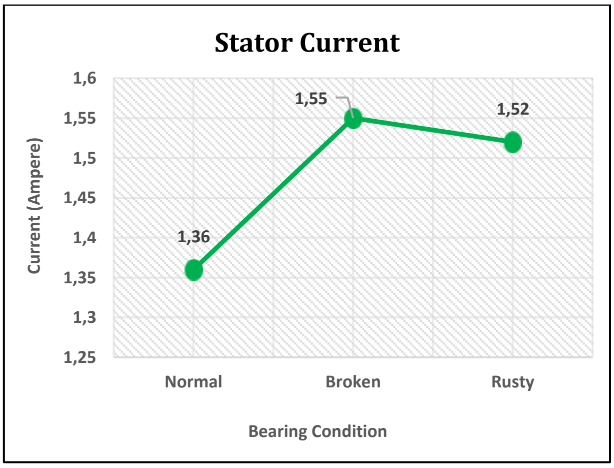

Figure 6. Stator current of 3-phase induction motor

Based on the results of measurement data for 14 days, the average in normal bearing conditions is 1,36 A, in broken bearing conditions 1,55 A and in rusty bearing conditions 1,52 A, the increase in current can also be caused by the loss of one of the voltages or several factors.

C. *Monitoring of Motor Efficiency*

From the results of 14 days of testing, the value of the supply voltage absorbed by the motor is measured on average, in normal bearing conditions the voltage is 404,2 V, in broken bearing conditions the average is 398,1 V and in rusty bearing conditions 392.4 V. Then In observing the power factor (Cos φ) value with normal bearing conditions it was 0,82, with rusty bearing conditions it was 0,66, and in the experiment with broken bearing conditions it had a value of 0,67, so this value corresponds to the standard stated on the motor nameplate in this condition. full load of 0,85.

Table 7. Power Factor of Multiple Bearing Failures

Day	Power Factor (Cos φ) Normal Bearing	Broken Bearing	Rusty Bearing
1	0,83	0,68	0,66
2	0,81	0,67	0,66
3	0,82	0,68	0,65
4	0,82	0,66	0,66
5	0,83	0,67	0,67
6	0,82	0,68	0,68
7	0,81	0,67	0,65
8	0,83	0,68	0,66
9	0,82	0,66	0,66
10	0,81	0,68	0,65
11	0,82	0,66	0,66
12	0,81	0,68	0,68
13	0,82	0,67	0,65
14	0,81	0,68	0,65

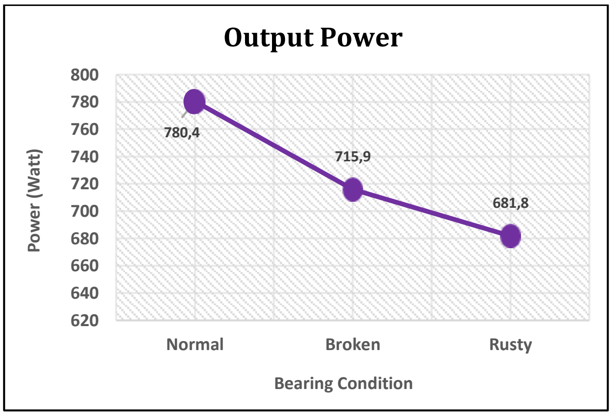

Figure 7. Output Power of 3-phase induction motor

The graph above shows that when the bearing conditions are normal, the power absorbed is 780,8 Watts, when a bearing breaks, the power absorbed is 715,9 Watts, and when a rusty bearing fails, the power is 681,8 Watts. The low power absorbed is due to the decreasing power factor value.

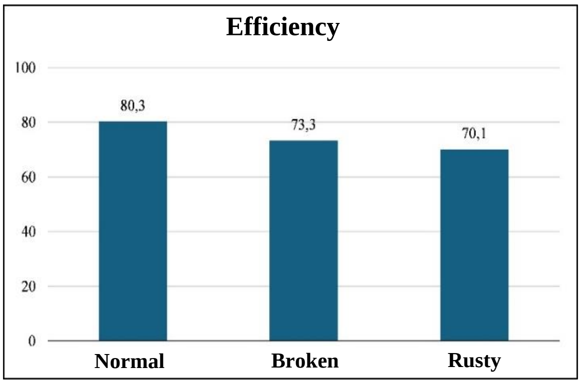

Figure 8. Efficiency of 3-Phase Induction Motor

Based on the efficiency value analysis with equation (2) above, the efficiency value in normal bearing conditions is calculated at 80,3% in good condition. Furthermore, the efficiency value in the condition of the ball bearing breaking fell to 73,7%. When the rusty ball bearing fails, the efficiency value also decreases, namely 70,1%. Figure 8 shows that the efficiency value for the experiment with normal ball bearing was still in good condition, whereas in other experiments, namely damaged ball bearings and rusty bearings, there was a decrease in efficiency.

D. Analysis of Experiment Results

From the experimental results with several types of failure in bearings in the first experiment with normal ball bearing conditions with a measured working voltage of 404,2 V, so the power absorbed was 780,4 Watts. Based on these conditions the resulting speed is 1481,2 rpm. For other parameters, the measured motor current was 1,36 A, and the hotspot temperature was 77,1^{0}C. In the second experiment with the type of bearing rupture failure, the measured working voltage was 398,1 V, so the power absorbed was 715,9 Watts. From this condition the resulting speed is 1432,2 rpm. For other parameters, the measured motor current was 1,55 A, and the hotspot temperature was 92,6^{0}C. The third experiment was with rusty bearing conditions, the measured voltage was 392,4 Volts and the power was 681,8 Watts, the current increased by 1,52 A and the temperature also increased by 88,2^{0}C. When the ball bearing rusts, the resulting speed is 1437,3 rpm. From experimental trials during normal conditions and when a malfunction the temperature will increase and the speed will decrease.

V. Conclusion

Based on the results of experiments with various types of bearing damage, it is possible to conclude that in normal bearing conditions, the voltage value measured is 404,2 V, the power absorbed is 780,4 Watts, the rotor speed is 1481,2 rpm, the motor current is 1,36 A, and the hotspot temperature is 77,10°C. In the second experiment with the kind of broken bearing, the voltage was 398,1 V, the power absorbed was 715,9 Watts, the speed was 1432,2 rpm, the motor current was 1,55 A, and the hotspot temperature was 92,60°C. During the third experiment with the rusty condition, the voltage was 392,4 V with a power of 681,8 Watt, the current was 1,52 A, and the temperature was 88,2°C with a speed of 1437,3 rpm. According to this experiment, temperature will increase and speed will decrease when in failure conditions.

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