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Experimental Study on Torque, Mechanical Power, and Efficiency of Electric Motors for Small Electric Cars

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ABSTRACT: *Electric vehicle is one of the vehicle solutions to overcome the dwindling availability of energy and reduce air pollution, by utilizing electric motor to convert electrical energy into mechanical energy. Analysis of the performance of an electric motor as a drive which includes mechanical power, torque, and efficiency is very fundamentally carried out to manage the use of energy consumption so that the performance and capacity of drive motor can be known. Based on this, the test was carried out to determine the effect of loading variations on torque, mechanical power and efficiency on electric motors as the drive of electric cars at the University of Mataram. The torque was testing by using the rope brake dynamometer method with load variations of 5 kg, 10 kg, and 15 kg carried out on the output shaft of the electric motor and the differential output shaft. The test results showed that the highest torque was obtained at a loading variation of 15 kg, namely 4.48 Nm in the electric motor and 5.81 Nm in the differential output shaft. In addition, the highest mechanical power was obtained at a load of 15 kg, namely 2264.92 Watts on an electric motor and 2271.45 Watts on a differential output shaft. While the highest efficiency is obtained at a load of 5 kg, namely 90.5% on an electric motor and 80.2% on a differential output shaft.*

Keywords: *Electric vehicle, Electric motor, Performance, Rope brake dynamometer, Torque*

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I. INTRODUCTION

The use of petroleum-based fuel as an energy source has increased significantly along with economic growth and improving public welfare. This phenomenon has a direct impact on the increasing need for transportation and industrial activities [1,9], while most energy supplies still depend on the combustion of non-renewable fossil fuels [2]. Based on data from the Central Statistics Agency in 2021, the number of vehicle ownership in Indonesia reached 143,797,227 units of various types, which indicates a high level of energy consumption in the transportation sector [3]. The combustion of fossil fuels produces harmful gas emissions such as carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbons (HC) which contribute to air pollution, global warming, and an increase in the greenhouse effect [9, 14]. This condition not only poses a threat to environmental quality but also impacts public health. Therefore, the urgency of developing sustainable alternative energy sources, such as electric vehicles and the use of renewable energy, is becoming increasingly important to reduce dependence on fossil fuels while minimizing negative impacts on the environment and supporting the achievement of sustainable development.

Although electric cars are widely recognized as environmentally friendly vehicles that do not produce exhaust emissions, their operation is constrained by the limited energy stored in the battery [4], which requires periodic recharging [8]. Current limitations in charging speed and battery capacity [5, 6] restrict the usability of most electric vehicles, thereby imposing boundaries on their operational range. In this context, energy consumption becomes a critical determinant of how far an electric car can travel [15]. Battery Electric Vehicles (BEVs) typically achieve a driving range of 100 to 250 km on a single full charge, while higher-class models can extend this distance to 300–500 km [7, 10]. However, empirical studies have demonstrated that actual energy consumption in electric vehicles is often higher than the manufacturer's stated values based on standardized driving cycles [10]. Research conducted by Pielecha et al. [11] further categorizes the factors influencing energy consumption into four main groups: driving style (including speed, acceleration, aerodynamics, and kinetic energy variations), road topology (such as slopes and curves), traffic density (congestion, toll roads, and road types), and environmental conditions (notably temperature).

To address the limited availability of fossil fuels and their environmental impacts, various environmentally friendly vehicles have been developed [7, 12], including electric cars. Electric cars are vehicles capable of converting electrical energy from batteries into mechanical energy or kinetic energy, thereby reducing dependence on fossil fuels while simultaneously reducing exhaust emissions [13,16]. The Indonesian government, through Presidential Regulation No. 55 of 2019 concerning the Acceleration of the Battery Electric Vehicle Program for road transportation, explicitly encourages universities and research institutions to play an active role in the development of electric vehicle technology through research, innovation, and implementation. Following up on this policy, the University of Mataram has conducted research and development on a city car-type electric vehicle intended as a vehicle for urban communities. This effort is expected to not only produce a prototype of an environmentally friendly alternative energy-based vehicle but also strengthen academic contributions in supporting the transition to a sustainable transportation system in Indonesia. Thus, the development of electric cars within universities is a strategic step in realizing technological innovation while supporting the national agenda regarding clean energy and emission reduction.

In designing electric vehicles, there are several main and supporting components that must be considered, one of which is the electric motor that functions as a converter of electrical energy from the battery into mechanical energy or kinetic energy [16]. Considering the crucial role of the electric motor in the electric car's propulsion system, an in-depth analysis is needed to evaluate the performance of the motor to be used. This analysis includes fundamental parameters such as mechanical power, torque, and efficiency, which play an important role in managing energy consumption and determining the performance and capacity of the drive motor. In line with these needs, this study was conducted to test the performance of the Permanent Magnet Synchronous Motor (PMSM) as an electric car propulsion system developed by the University of Mataram. Testing was carried out using the rope brake dynamometer method under various loads, so that empirical data can be obtained regarding the characteristics of torque, mechanical power, and motor efficiency. The results of the analysis are expected to contribute to the understanding of electric motor performance in the context of electric vehicles, while supporting the development of environmentally friendly transportation technologies based on alternative energy.

II. EXPERIMENTAL SETUP

The method used in this study is an experimental method, namely a method that aims to test the effect of one variable on another variable. In this study, the effect of load variations on the performance of a permanent magnet synchronous motor (PMSM) will be analyzed, namely torque, mechanical power, and efficiency using the rope brake dynamometer method. The design of the equipment used in the test can be seen in Figure 1 below.

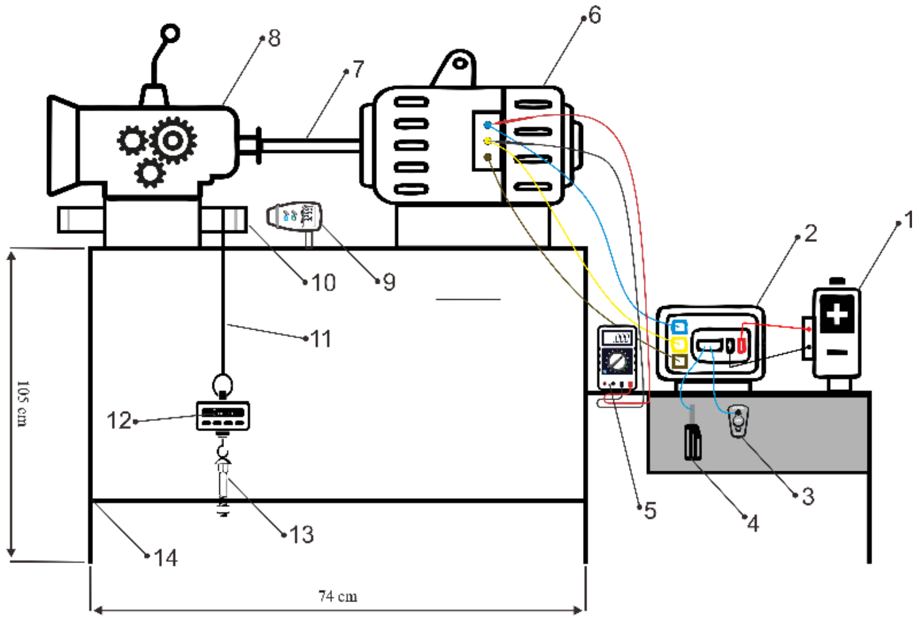

Figure 1 Sketch of the testing tool. 1. Battery, 2. Motor controller, 3. Forward and reverse lever, 4. Gas pedal, 5. Digital multimeter, 6. Electric motor, 7. Connecting shaft, 8. Differential gear box, 9. Digital tachometer, 10. Differential output shaft, 11. Steel sling, 12. Digital Spring balance, 13. Load adjusting bolt, 14. Mounting frame.

Figure 2 Testing equipment

The stages carried out in the research are the first stage, the power in the battery is input to the electric motor then the electric motor is given rotation at full throttle conditions with variations in loading, namely 5 kg, 10 kg and 15 kg on the output shaft of the electric motor. The second stage, measuring the electric voltage and electric current using an digital multimeter measuring instrument as input data on the motor. The third stage, recording the magnitude of the rotation that occurs on the output shaft of the electric motor in each variation of loading using a tachometer and recording the magnitude of the load mass read based on the rope brake dynamometer method on a digital spring balance measuring instrument. Furthermore, the same stages are carried out on the differential output shaft test.

There are several equations used to analyze experimental data, as follows. Based on the rope brake system method used, the following equation can be used to determine the torque value:

$$T = (Wt - Ws) \times g \times (D+d)/2 \quad (1)$$

Wt shows the reading of the loading value on the dead weight, Ws shows the reading of the loading value on the spring balance, g is the acceleration of gravity on the earth, D shows the diameter of the pulley and d shows the diameter of the rope brake.

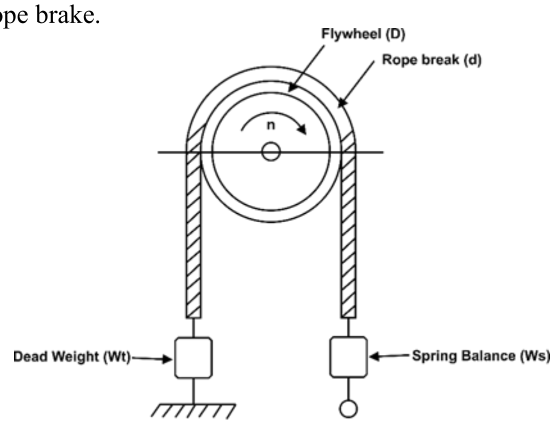

Figure 3 Rope brake dynamometer system

The mechanical power of an electric motor can be determined using the following equation [5]:

$$Pout = T \times (2 \times \pi \times n)/60 \quad (2)$$

T is the value of torque, and n indicates the value of motor rotation.

Meanwhile, efficiency is the comparison of the output power (Pout) used to the input power (Pin) at the terminal, which can be formulated as follows [6]:

$$\eta = Pout/Pin \times 100\% \quad (3)$$

III. RESULTS AND DISCUSSION

After testing, the results obtained were displayed in a graph containing the effect of variations in the loading mass of 5 kg, 10 kg and 15 kg on torque, mechanical power and efficiency in electric motor testing and differential testing, which can be seen in the graph below.

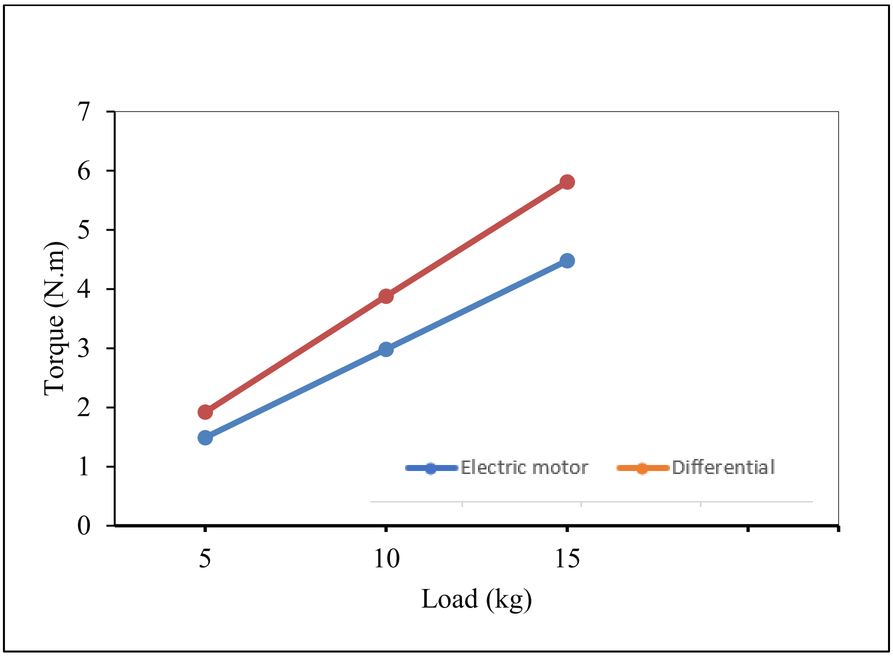

Figure 4 Relationship between load mass and torque in electric motor and differential tests

Figure 4 shows a direct relationship between the load mass and torque. The greater the load, the greater the resulting torque. This is because the torque equation states that the load is directly proportional to the torque value. The greater the load, the greater the torque value. Furthermore, due to the load, the rotational speed of the shaft will decrease, so the resulting torque tends to increase.

Graph 4 shows the relationship between load variations and the torque generated by the electric motor and differential output shaft. In general, it can be seen that increasing the load results in an increase in torque; the greater the load, the greater the resistance force that must be overcome by the motor and differential. At a load of 5 kg, the torque in the electric motor is 1.49 N m, while the differential reaches 1.92 N m. At a load of 15 kg, the electric motor produces 4.48 N m while the differential reaches 5.81 N m. This confirms that the differential system functions to increase the torque transmitted to the wheels so that the vehicle can carry a greater load. Thus, this figure 4. illustrates that load variations directly affect the increase in torque, and demonstrates the important role of the differential in strengthening the propulsion of electric vehicles.

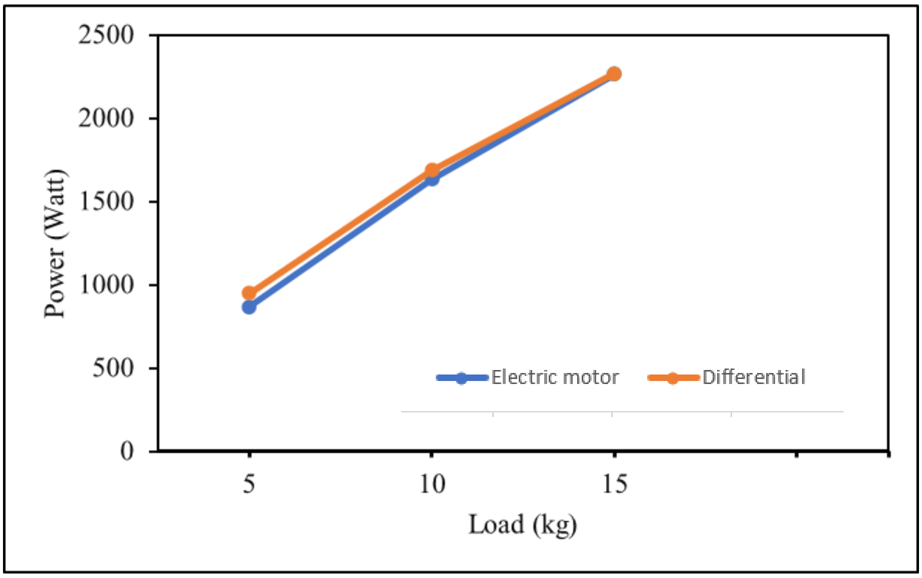

Figure 5 Relationship between load and mechanical power in electric motor and differential tests

Figure 5 shows that the greater the load mass, the greater the mechanical power produced. This is because mechanical power is influenced by the magnitude of the torque. From the previous results, the greater the load, the greater the torque, so the greater the torque resulting from the load will affect the amount of mechanical power produced by the electric motor. The test results show that increasing the loading mass is directly proportional to the increase in mechanical power generated. The highest power was achieved at a loading mass of 15 kg, which was 2271.45 Watts in the electric motor test and 2264.92 Watts in the differential test. At a loading mass of 10 kg, the mechanical power obtained was 1653.66 Watts for the electric motor and 1688.99 Watts for the differential. Meanwhile, the lowest power was recorded at a loading mass of 5 kg, with a value of 870.69 Watts for the electric motor and 950.15 Watts for the differential. In general, this trend indicates that the greater the loading mass, the higher the mechanical power the system can produce. This shows the consistency of performance in both the electric motor and differential tests, and confirms that the workload has a significant influence on mechanical power output.

The greater the load, the higher the torque required to maintain system rotation. This implies an increase in output power, as long as the motor can provide sufficient energy to overcome the load resistance. The consistency of the results between the electric motor and differential tests also indicates that the transmission system is performing efficiently in transferring energy from the motor to the load. These findings have practical relevance in the context of designing electric motor-based power systems. The increase in power with increasing load indicates potential applications in real-world operating conditions, where the motor must be able to adapt its performance to load variations. Furthermore, the agreement between the electric motor and differential results confirms that the integration of both components can support overall system efficiency. Thus, this study not only confirms the theoretical relationship between load and power but also provides an empirical basis for the development of more adaptive and sustainable power systems.

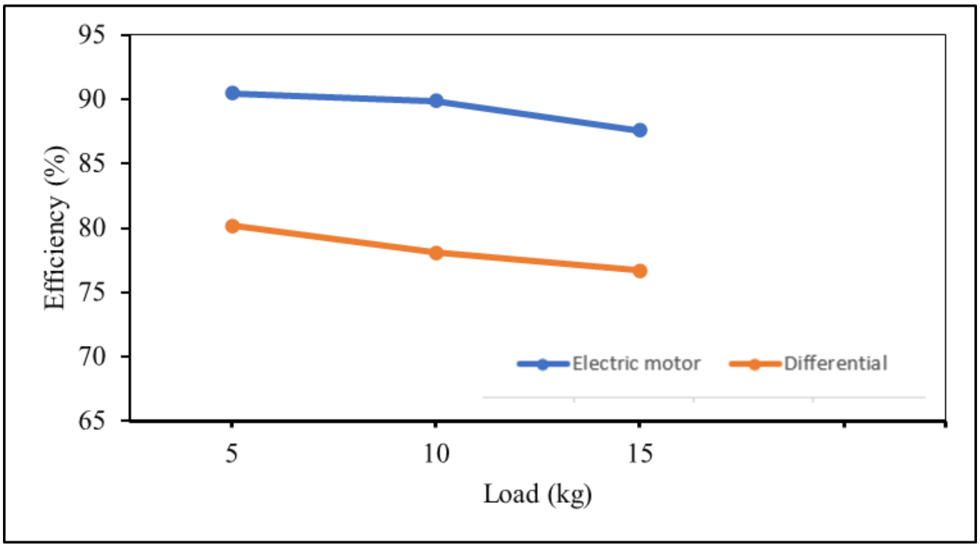

Figure 6 Relationship between load mass and efficiency in electric motor and differential testing.

Figure 6 above shows an inverse relationship between efficiency and load, meaning the greater the load mass, the lower the efficiency level. This is because the greater the load applied to the electric motor shaft, the motor rotation will decrease but the torque will be higher, resulting in slippage and heat losses. This is in accordance with research [7], where if the torque produced is large, the slip and current will automatically increase. This larger current is due to the motor load, which will reduce the efficiency of the electric motor. System efficiency is determined by comparing the motor output power with the input power at the terminal, thus determining the performance level of the electric motor and differential in delivering energy. Test results show a decreasing trend in efficiency as the load mass increases. The highest efficiency was obtained at a load mass of 5 kg, which was 90.5% in the electric motor test and 80.2% in the differential test. At a load mass of 10 kg, the efficiency decreased to 89.3% for the electric motor and 77.9% for the differential. The lowest efficiency value was recorded at a load mass of 15 kg, which was 87.6% for the electric motor and 76.8% for the differential.

The decrease in efficiency at higher loads can be explained by increased energy losses due to the increased torque and mechanical resistance the system must overcome. This results in some of the input energy not being fully converted into useful output power. The difference in efficiency values between the electric motor and the differential also indicates additional losses in the transmission system, which can include friction, component deformation, and load imbalance. These findings confirm that although mechanical power increases with increasing load, system efficiency actually decreases. Thus, there is a trade-off between the ability to generate high power and efficiency stability. The practical implication of these results is the need to optimize the design of motors and transmission systems to maintain high efficiency under greater load variations. Furthermore, this research provides an empirical basis for the development of more adaptive electric motor-based power systems, considering the balance between output power and energy efficiency.

The decreasing efficiency value due to the addition of the load is because the greater the load given to the electric motor shaft, the motor rotation will decrease but the torque will be higher, resulting in slip and heat losses. This is in accordance with the research of Antonov et al. in 2016. If the generated torque is large, then automatically the slip and current will be greater. This larger current is due to the motor load so it will reduce the efficiency of the electric motor.

IV. CONCLUSION

The magnitude of the load variation will affect the amount of torque, mechanical power and efficiency level produced in the electric motor and differential tests. The highest torque value was obtained at a load of 15 kg, which was 4.48 Nm in the electric motor test and 5.81 Nm in the differential test, this is because the greater the load will cause a decrease in rotation due to friction so that it will increase the amount of torque. In addition, the higher the load, the greater the mechanical power required, the highest mechanical power was obtained at a load of 15 kg, namely 2264.92 watts in the electric motor test and 2271.45 Watts in the differential test. This is because the amount of mechanical power is influenced by the amount of torque, the greater the torque due to the amount of loading, the greater the mechanical power of the electric motor. The level of efficiency in electric motors is influenced by the presence of loading, the greater the loading, the lower the efficiency level, the highest efficiency was obtained at a load of 5 kg, namely 90.5% in the electric motor test and 80.2% in the differential test. This is because the additional load causes the slip to increase, thereby reducing the efficiency level.

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