Journal of Mechatronics and Artificial Intelligence 3(1)(2026)57-70

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Journal of Mechatronics and Artificial Intelligence

JMAI JOURNAL OF MECHATRONICS AND ARTIFICIAL INTELLIGENCE

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Efficiency Evaluation of a DC Generator Using Experimental Loss Measurements

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ARTICLE INFO

Article History:

Submitted/Received 5 June 2026
Accepted 15 June 2026
Publication Date 30 June 2026

Keywords:
Copper loss,
DC generator,
Efficiency,
Friction loss,
Iron loss

ABSTRACT

This study evaluates the efficiency of a DC generator using experimental loss measurements based on a two-identical-machine method. Two identical DC machines were mechanically coupled, with one machine operated as the driving motor and the other as the generator under test. The total loss was determined from the difference between the motor input power and the generator output power, while the copper loss was calculated using the armature resistance obtained from a locked-rotor test. Since the generator did not have a field winding, only armature copper loss was considered. The friction loss was estimated from the no-load test, and the iron loss was determined using a residual loss method. The experimental results showed that the generator output power increased from 0.0064 W at 1.5 V to 1.8032 W at 5.0 V. The generator efficiency also increased with operating voltage, reaching a maximum value of 63.96% at 5.0 V. Copper loss increased significantly with load current and became a dominant loss component at higher operating conditions. The residual iron loss showed positive values at low voltage levels but became negative at higher voltages, indicating limitations in separating friction and iron losses using the current method. Overall, the proposed experimental approach was effective for evaluating the efficiency trend and identifying the dominant loss behavior of the DC generator, although further refinement is required to separate mechanical and magnetic losses more accurately.

1. Introduction

Direct current (DC) generators are still widely used in educational laboratories, small-scale energy conversion systems, battery charging applications, and experimental renewable energy systems [1]. Although many modern power generation systems employ AC generators and power electronic converters, DC generators remain important because their electrical output characteristics are relatively simple to observe and analyze [2]. This makes them suitable for studying the fundamental relationship between mechanical input power, electrical output power, and internal power losses in electromechanical energy conversion.

Efficiency is one of the most important indicators for evaluating generator performance [3]. In an ideal generator, all mechanical input power would be converted into useful electrical output power [4]. However, practical DC generators experience several internal losses, including armature copper loss, field copper loss, brush contact loss, iron or core loss, mechanical friction loss, windage loss, and stray loss [5]. These losses reduce the amount of useful output power and directly influence the overall efficiency of the generator [6]. Therefore, measuring and analyzing generator losses is essential for understanding the actual performance of a DC generator under operating conditions.

Previous standards and studies have emphasized the importance of loss-based efficiency evaluation in rotating electrical machines. IEC 60034-2-1:2024 provides standard methods for determining losses and efficiency from experimental tests and is applicable to DC machines as well as AC synchronous and induction machines [7]. Similarly, IEEE Std 113-1985 provides test procedures for evaluating the performance characteristics of conventional direct-current machines [8]. These standards show that efficiency evaluation should not rely only on the final input-output power comparison but should also consider specific loss components that occur inside the machine.

Several previous studies have investigated experimental methods for evaluating DC machine performance and generator losses. Soong [9] demonstrated that stall and no-load tests can be used to characterize brushed DC permanent-magnet machines by identifying armature resistance, back-EMF constant, and no-load loss torque. These parameters can then be used to predict machine performance and construct an efficiency map over different torque and speed conditions. This approach highlights the value of experimental parameter measurement for understanding how DC machine efficiency varies with operating conditions.

In the context of renewable energy applications, Irawan et al. [10] investigated loss components in DC generators used for wind turbine applications. Their study considered ohmic losses, magnetic core losses, and mechanical losses through experimental testing and simulation. The reported results showed significant total power loss, emphasizing the importance of careful loss assessment when DC generators are used in small wind energy systems. Similarly, Irasari [10] examined the feasibility of using a car alternator as a generator for wind turbine applications. The study reported an alternator efficiency of approximately 50% and a corrected cut-in wind speed of 6.35 m/s, indicating that generator selection and loss characteristics strongly affect the feasibility of small-scale wind energy systems. Jessam also experimentally investigated AC and DC generators connected to a Savonius-type wind turbine using discharged air from an air conditioner blower, where the DC generator produced 46 V, 0.32 A, and 14.72 W under a 3 HP air conditioner condition.

Although previous studies have discussed DC machine testing, generator output performance, and generator applications in wind energy systems, there is still a need for a clear experimental evaluation that focuses specifically on the relationship between measured loss components and DC generator efficiency. Many studies report output voltage, current, power, or system feasibility, but fewer studies explain how individual losses contribute to the final efficiency value under controlled experimental conditions. A loss-based evaluation can provide a more detailed understanding of which loss components dominate and how they change with loading conditions.

Therefore, this study aims to evaluate the efficiency of a DC generator using experimental loss measurements. The main objective is to determine the major loss components of the generator and analyze their influence on overall efficiency. By measuring electrical parameters and estimating loss components experimentally, this study provides a practical approach for understanding DC generator performance. The results are expected to support both educational laboratory analysis and small-scale generator performance evaluation, particularly in applications where efficiency and power loss must be carefully considered.

2. Methods

2.1. Experimental overview

This study evaluates the efficiency of a DC generator based on experimentally measured loss components, including total power loss, copper loss, friction loss, and iron loss. The evaluation was carried out using a two-machine method, in which two identical DC generators were mechanically coupled through a common shaft. One machine was operated as the driving machine, while the other machine was operated as the generator under test.

The two machines were selected with identical ratings and construction characteristics so that their losses could be assumed to be approximately equal when operated at the same rotational speed. This assumption is important because the total loss measured from the coupled system is divided equally between the two machines. Before conducting the load test, the armature and field winding resistances were measured to support the calculation of copper losses. The general concept of the experimental system is shown in Figure 1.

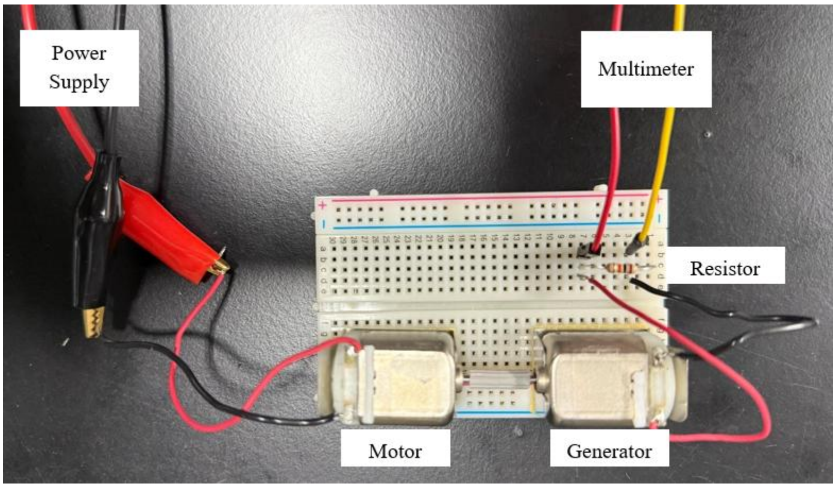

Figure 1: Schematic diagram of the two-identical-DC-generator experimental setup

2.2. Two-Generator Loss Measurement Method

The two-generator method is based on the power balance of the coupled machine system. Electrical power is supplied to the first DC machine, which operates as a motor and drives the second DC machine. The second machine operates as a generator and delivers electrical power to a resistive load. During the experiment, the input voltage and current of the driving machine, the output voltage and current of the generator, and the rotational speed of the shaft were measured for each load condition.

The electrical input power supplied to the driving machine is calculated as:

$$P_{in} = \mathrm{V}_{in} \cdot I_{in} \tag{1}$$

where P_{in} is the electrical input power [W], V_{in} is the input voltage [V], and I_{in} is the input current [A]. The electrical output power of the generator under test is calculated as:

$$P_{out} = \mathrm{V}_{out} \cdot I_{out} \tag{2}$$

where P_{out} is the generator output power [W], V_{out} is the terminal output voltage [V], and I_{out} is the load current [A]. The difference between the electrical input power and electrical output power represents the total loss of the two-machine system ($P_{loss,system}$) in Watt:

$$P_{loss,system} = \mathrm{P}_{out} - P_{in} \tag{3}$$

Since the two machines are identical and operate under the same mechanical speed, the total power loss of one DC generator is estimated as:

$$P_{loss,total} = \frac{P_{loss,system}}{2} \tag{4}$$

where $P_{loss,total}$ represents the total power loss of one DC generator [W].

2.3. Copper Loss Measurement

Copper loss occurs due to the electrical resistance of the armature winding. In this study, the copper loss was determined using a locked-rotor test, also known as a stall test. In this test, the shaft of the DC machine was mechanically held so that the rotor could not rotate as shown in Figure 2.

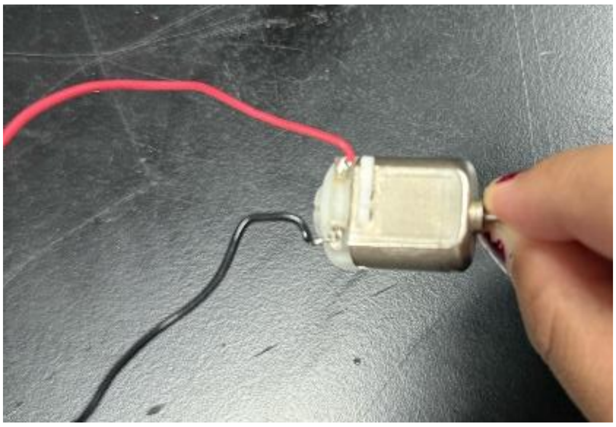

Figure 2: Locked-test.

Under this condition, the rotational speed was zero and no back electromotive force was generated. Therefore, the applied voltage was mainly used to overcome the internal armature resistance.

During the locked-rotor test, a low DC voltage was gradually applied to the armature circuit while the corresponding armature current was measured. A low voltage was used to avoid excessive current and prevent overheating of the winding. The armature resistance was then obtained from the measured voltage and current as:

$$R_a = \frac{V_{lock}}{I_{lock}} \tag{5}$$

where R_a is the armature resistance [Ω], V_{lock} is the applied voltage during the locked-rotor test [V], and I_{lock} is the measured current under the locked-rotor condition [A]. After the armature resistance was obtained, the copper loss under each load condition was calculated as:

$$P_{Cu} = {I_a}^2 \cdot R_a \tag{6}$$

where P_{Cu} is the copper loss [W] and I_a is the armature current during generator operation [A].

2.4. Friction Loss Measurement

Friction loss is the mechanical loss caused by the rotating parts of the DC generator, including bearing friction, brush friction, and mechanical contact in the shaft system. In this study, the friction loss was estimated from the no-load operation of the coupled machines. During the no-load test, the generator terminal was kept open so that no external load current flowed through the generator circuit. The coupled machines were rotated at the selected operating speed, and the input voltage and input current of the driving machine were measured. The experiment is shown as Figure 3.

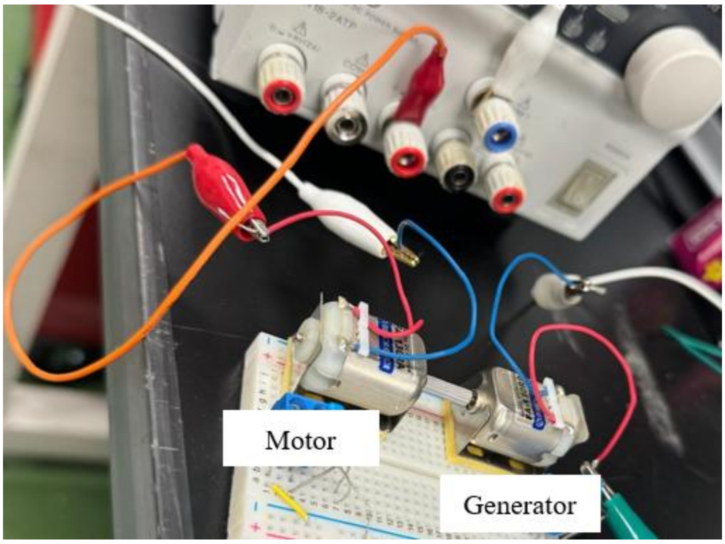

Figure 3: Friction loss measurement.

The no-load input power is calculated as:

$$P_{in,0} = V_{in,0} \cdot I_{in,0} \tag{7}$$

where $P_{in,0}$ is the no-load input power [W], $V_{in,0}$ is the input voltage during no-load operation [V], and $I_{in,0}$ is the input current during no-load operation [A]. The no-load copper loss of the driving machine ($P_{Cu,0}$) in Watt is calculated as:

$$P_{Cu,0} = {I_{in,0}}^2 \cdot R_a \tag{8}$$

After subtracting the no-load copper loss from the no-load input power, the remaining power represents the rotational loss of the two-machine system ($P_{rot,system}$) in Watt:

$$P_{rot,system} = P_{in,0} - P_{Cu,0} \tag{9}$$

Because the two machines are identical, the rotational loss of one machine (P_{rot}) in Watt is estimated as:

$$P_{rot} = \frac{P_{rot,system}}{2} \tag{10}$$

In a DC generator without field winding, the no-load rotational loss may contain both mechanical friction loss and iron loss. Therefore, to use only three loss components in this study, the friction loss was estimated from the mechanical part of the no-load rotational loss, while the remaining part was treated as iron loss through residual calculation. Thus, the friction loss (P_{fric}) in Watt is expressed as:

$$P_{fric} = P_{rot} - P_{iron,0} \tag{11}$$

However, because $P_{iron,0}$ cannot be directly eliminated in a generator without field winding, the practical implementation in this study estimates friction loss from the no-load mechanical rotational component and calculates iron loss as the residual component of the total measured loss.

2.5. Iron Loss Determination

Iron loss is caused by hysteresis and eddy current effects in the magnetic core of the DC generator. Since the generator used in this study does not have a field winding, the magnetic flux cannot be reduced to zero during the no-load test. Therefore, iron loss was not measured directly but was determined using a residual loss method. After obtaining the total loss, copper loss, and friction loss, the iron loss was calculated as:

$$P_{iron} = P_{loss,total} - P_{Cu} - P_{fric} \tag{12}$$

where P_{iron} is the iron loss [W], $P_{loss,total}$ is the total loss of one generator [W], P_{Cu} is the copper loss obtained from the locked-rotor test [W], and P_{fric} is the friction loss [W].

2.6. Efficiency Calculation

The efficiency of the DC generator was calculated using the output power and the total measured loss. The mechanical input power to the generator was estimated as the sum of the electrical output power and the total loss:

$$P_{mech,in} = P_{out} + P_{loss,total} \tag{13}$$

Therefore, the efficiency is calculated as:

$$\eta = \frac{P_{out}}{P_{mech,in}} 100\% \tag{14}$$

where η is the generator efficiency, P_{out} is the electrical output power [W], and $P_{loss,total}$ is the total loss of one generator [W].

3. Results and Discussion

3.1. Results

3.1.1. Armature Resistance from the Locked-Rotor Test

The locked-rotor test was conducted to determine the armature resistance of the DC machine. During this test, the rotor was mechanically held so that no back electromotive force was generated. The applied voltage and current were then used to calculate the armature resistance. The measured armature resistance values are shown in Table 1.

Table 1: Armature resistance obtained from the locked-rotor test

Voltage [V]	Current [A]	Power [W]	Armature Resistance [Ω]
1.0	0.26	0.26	3.85
2.0	0.53	1.06	3.78
3.0	0.80	2.40	3.75
4.0	1.06	4.24	3.77
Average			3.78

3.1.2. No-Load Characteristics

The no-load test was performed to observe the generated voltage and rotational speed characteristics of the generator without external loading. The results show that the generated voltage increased almost linearly with angular speed as Figure 4. As the angular speed increased from 43.96 rad/s to 384.34 rad/s, the no-load generated voltage increased from 0.486 V to 4.29 V. This trend indicates that the generator exhibited a nearly proportional relationship between speed and induced voltage, which is consistent with the basic principle of DC generation.

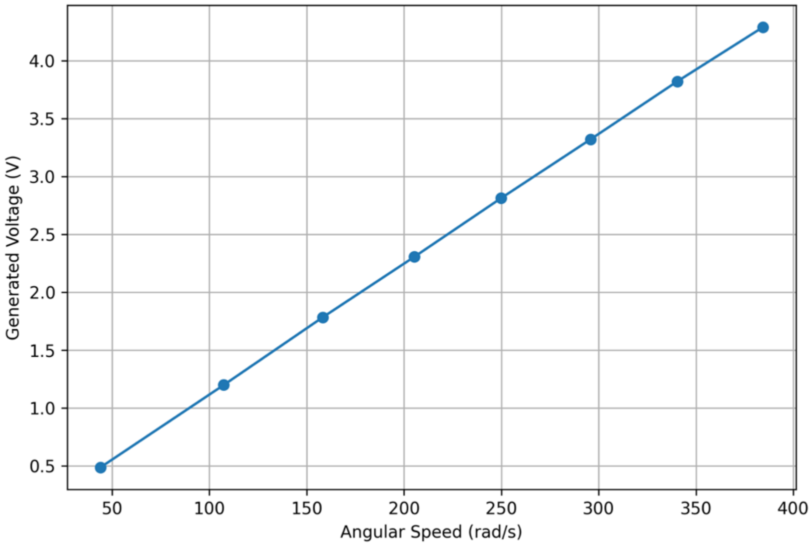

Figure 4: No-load generated voltage versus angular speed.

3.1.3. Load Test Results

The load test was carried out using two identical DC machines mechanically coupled through a common shaft. One machine operated as the driving motor and the other as the generator under test. The total loss of one generator was estimated as half of the difference between the motor input power and the generator output power. The results show that both the motor input power and the generator output power increased with increasing motor voltage as shown in Figure 5. The generator output power rose from 0.0064 W at 1.5 V to 1.8032 W at 5.0 V. At the same time, the estimated total loss per generator increased from 0.2413 W to 1.0159 W. The efficiency also improved significantly with increasing voltage as shown in Figure 6. The lowest efficiency was observed at 1.5 V, with a value of only 2.59%, while the highest efficiency was obtained at 5.0 V, reaching 63.96%.

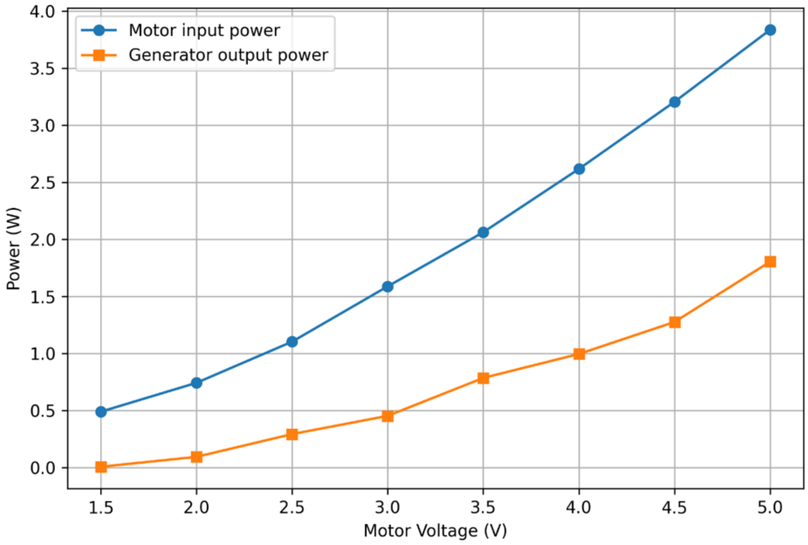

Figure 5: Input and output power versus motor voltage.

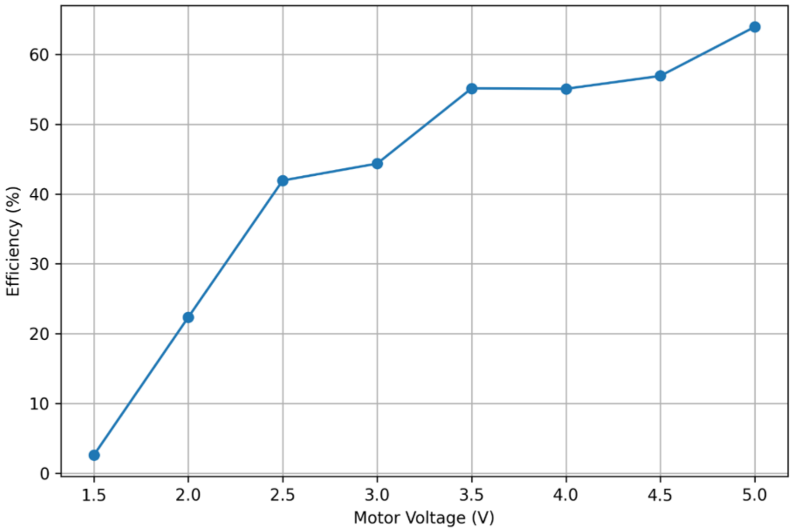

Figure 6: Generator efficiency versus motor voltage.

3.1.4. Loss Component Results

Using the armature resistance obtained from the locked-rotor test, the copper loss was calculated for each loading condition. The experimental data is shown by Figure 7. The copper loss increased rapidly with current, from 0.0015 W at 0.02 A to 1.1872 W at 0.56 A. The friction loss was estimated from the no-load test results. The estimated friction loss increased gradually with operating voltage, ranging from 0.0724 W at 1.5 V to 0.4415 W at 5.0 V.

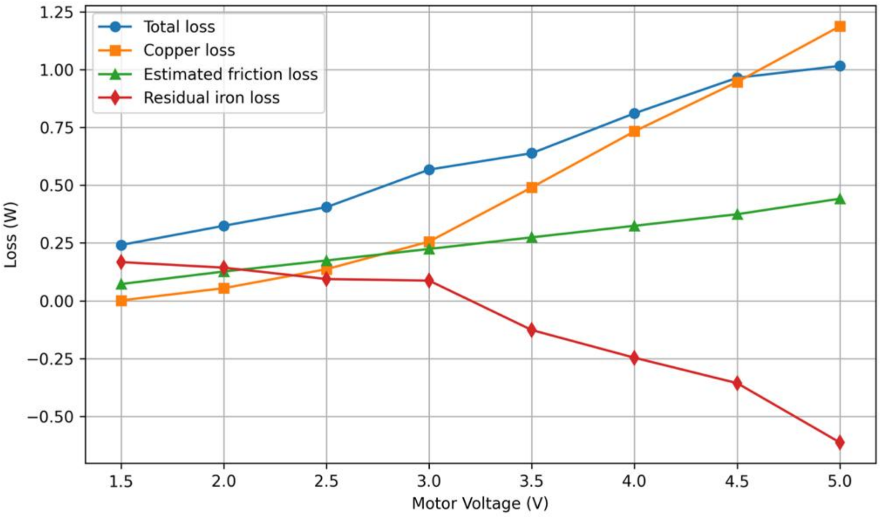

Figure 7: Loss components versus motor voltage

The iron loss was then obtained using the residual loss method. Positive residual iron loss values were obtained at low operating voltages, namely 0.1674 W at 1.5 V, 0.1433 W at 2.0 V, 0.0940 W at 2.5 V, and 0.0871 W at 3.0 V. However, for voltages of 3.5 V and above, the calculated iron loss became negative. The negative residual iron loss observed at higher operating voltages indicates a limitation in the loss separation method. Since iron loss was calculated as a residual value, it became negative when the sum of copper loss and estimated friction loss exceeded the measured total loss. Physically, iron loss cannot be negative. Therefore, this result suggests that the no-load-based friction loss estimation may still contain part of the iron loss. This occurs because the tested generator has no field winding, so the magnetic flux cannot be reduced to zero during the no-load test. Consequently, the calculated iron loss should be interpreted as an effective residual value rather than a directly measured pure iron loss.

3.1.5. Summary of Experimental Results

To provide a comprehensive overview of the experimental results, the measured and calculated values from the load test were summarized in table 2. The summary includes the motor input power, generator output power, total loss per generator, efficiency, copper loss, estimated friction loss, and residual iron loss for each operating voltage. The total loss was calculated using the two-identical-machine method, while the copper loss was obtained from the armature resistance measured during the locked-rotor test. The friction loss was estimated from the no-load test, and the iron loss was calculated as the residual loss after subtracting copper and friction losses from the total loss. This summary allows the relationship between operating voltage, output power, loss components, and generator efficiency to be observed more clearly.

Table 2: Summary of power, losses, and efficiency

Motor Voltage [V]	Input Power (P_{in}) [W]	Output Power (P_{out}) [W]	Total Loss ($P_{loss,total}$) [W]	Efficiency [%]	Copper Loss (P_{Cu}) [W]	Friction Loss (P_{fric}) [W]	Residual Iron Loss (P_{iron}) [W]
1.5	0.49	0.006	0.24	2.59	0.002	0.07	0.17
2.0	0.74	0.093	0.32	22.35	0.054	0.13	0.14
2.5	1.10	0.293	0.40	41.95	0.137	0.17	0.09
3.0	1.59	0.452	0.57	44.37	0.256	0.22	0.08
3.5	2.06	0.785	0.64	55.15	0.491	0.27	-0.13
4.0	2.62	0.994	0.81	55.09	0.733	0.32	-0.25
4.5	3.20	1.275	0.96	56.93	0.947	0.37	-0.36
5.0	3.83	1.803	1.02	63.96	1.187	0.44	-0.61

3.2. Discussion

3.2.1. Power and Efficiency Characteristics

The results indicate that the generator performance improved as the applied motor voltage increased. At low operating voltages, the output power remained very small compared with the input power, resulting in very low efficiency. This suggests that, under low-load conditions, internal losses consumed a large fraction of the supplied power. As the operating voltage increased, the output power increased more rapidly than the total loss, which caused the efficiency to improve. The highest efficiency of 63.96% was obtained at 5.0 V, indicating that the generator operated more effectively at higher loading conditions.

3.2.2. Copper Loss Behaviour

The copper loss increased substantially with increasing load current, which is expected because it is proportional to the square of the armature current. At low current, the copper loss was negligible, but at higher current levels it became one of the dominant loss components. This result suggests that winding resistance plays an important role in limiting generator efficiency at higher loads. The trend also indicates that thermal effects may become relevant at higher operating currents, since increased temperature would further increase the armature resistance and consequently the copper loss.

3.2.3. Friction Loss and Its Interpretation

The estimated friction loss increased gradually with motor voltage and speed. This trend is physically reasonable because higher speed generally results in greater mechanical losses due to bearing friction, brush contact, and aerodynamic drag. Therefore, the observed increase in estimated friction loss is consistent with the expected rotational behaviour of the machine. However, since the machine does not have a field winding, the no-load test could not eliminate magnetic effects. As a result, the estimated friction loss obtained from the no-load test may still include a portion of iron loss. Thus, the reported friction loss should be interpreted as an experimentally estimated mechanical loss component rather than a perfectly isolated pure friction loss.

3.2.4. Iron Loss Estimation and Method Limitation

The residual iron loss values were positive only at lower operating voltages and became negative at higher voltages. A negative iron loss is not physically possible, which indicates that the separation of copper loss, friction loss, and iron loss was not fully accurate under all operating conditions. This result suggests that the no-load-based friction loss estimation likely overestimated the pure mechanical loss at higher voltages, because the no-load power still included magnetic core losses. Consequently, when copper loss and estimated friction loss were subtracted from the total loss, the remaining residual iron loss became negative. Therefore, the iron loss values reported in this study should be interpreted as residual iron loss estimates, rather than directly measured pure iron losses. Despite this limitation, the overall results still provide useful insight into the loss distribution and efficiency behaviour of the DC generator.

3.2.5. Overall Interpretation

Overall, the results show that the efficiency of the tested DC generator increased with motor voltage and output power. Copper loss became increasingly dominant at higher load currents, while the estimated friction loss increased with speed. The residual iron loss calculation revealed a limitation of the proposed separation method, especially for a DC generator without a field winding. Nevertheless, the two-identical-machine method combined with the locked-rotor and no-load tests was effective for evaluating the overall efficiency trend and the major loss characteristics of the generator. The method is therefore useful as an experimental approach for practical generator performance evaluation, although more refined techniques are required to separate friction and iron losses more accurately.

4. Conclusion

This study evaluated the efficiency of a DC generator using experimental loss measurements based on a two-identical-machine method. The total loss was obtained from the difference between the motor input power and generator output power, while the copper loss was calculated using the armature resistance obtained from the locked-rotor test. The friction loss was estimated from the no-load test, and the iron loss was determined using a residual loss method. The results showed that the generator output power increased from 0.0064 W at 1.5 V to 1.8032 W at 5.0 V, while the efficiency improved from 2.59% to a maximum value of 63.96%. Copper loss increased significantly with load current and became one of the dominant loss components at higher operating conditions. The estimated friction loss also increased with speed, indicating the influence of mechanical rotational effects. However, the residual iron loss became negative at higher voltage levels, suggesting that the separation between friction and iron losses was limited by the experimental method, particularly because the generator did not have a field winding to eliminate magnetic flux during no-load testing. Overall, the proposed method was effective for evaluating the general efficiency trend and identifying the dominant loss behaviour of the DC generator, although further refinement is required to separate friction and iron losses more accurately.

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