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Electric Machines Virtual Laboratory: Testing of DC Motor

R Badarudin[1], D Hariyanto[2], M Ali[3], and S Meunmany[4]

[1,2,3] Department of Electrical Engineering Education, Faculty of Engineering, Universitas Negeri Yogyakarta, Indonesia
[4] Department of Technical and Vocational Education, Ministry of Education and Sports, Lao PDR

E-mail: [1] rohjai.badarudin@uny.ac.id; [2] didik_hr@uny.ac.id; [3] muhal@uny.ac.id; [4] santiphap.m@moes.edu.la

Abstract. This article describes the realization of testing the characteristics of a DC motor on Simulink as a virtual laboratory. Testing of DC motors based on real conditions in a physical laboratory by combining two DC machines coupled to shafts including DC motors and DC generators. The types of DC motors tested include separately excited DC motors, shunt DC motors, and series DC motors. The implementation of the Simulink model adopts the wiring diagram in the real test. The test procedure is also adopted on the real test procedure. The data from the test results are made in DC motor characteristics graph. Virtual laboratory using Simulink can be used to realize DC motor testing, including test procedures, running no-load DC motors, increasing the load of DC motors with infinitely simulation features on Simulink. The results of the study show the characteristics of the experimental data for all types of DC motors tested according to the theory.

1. Introduction

Mechanical energy can be generated by converting electrical energy using an electric motor [1]. The application of DC motors in everyday life is very wide and is still used today. For the need for constant rotation, adjustable speed, a DC motor is a type of motor that is very easy to adjust the rotational speed of the rotor. DC motors produce mechanical energy by converting DC power source [2]. The types of DC motors include separately excited DC motors, shunt motors, series motors, and compound motors. Separately excited DC motors and shunt DC motors are widely used for purposes that require constant rotation, while series DC motors are widely used for purposes that require high torque. Selection of the type of DC motor is needed so that the characteristics of the DC motor are in accordance with the needs of the machine. The main advantage of the DC motor over other motors is the ease of controlling the armature speed. The DC motor armature speed regulation range can be set at a variable source voltage or varying the voltage across the field windings [3], [4].

Experimental simulation is a format for presenting concepts that try to match the dynamic processes that occur in the real world [5]. A virtual environment is a digitally replica version of something real. Replication of the real form into a digital model is made using computer software. The results of replication may not be similar to the real world, but it is enough to describe something abstract into reality [6], [7]. Simulation is used when the actual system cannot be involved for several reasons, including the system is inaccessible, the system is dangerous or unacceptable for human

security, and the system is in the design stage. The concept of virtual simulation applied in this research is to test a DC motor. The characteristics of a DC motor will be tested, including separately excited DC motor, shunt DC motor, and series DC motor. The test was carried out using a simulation of the motor-generator model on Simulink [8]. The DC motor test procedure includes 1) running the DC motor from 0 rpm to nominal speed at nominal voltage, 2) loading the DC motor coupled to a DC generator, 3) the process of increasing the load gradually until data is obtained in the form of armature current, armature speed, and armature torque. The testing procedure in the simulation is adapted from the test procedure using real equipment, so it is hoped that the testing process will be as expected.

2. Literature Review

Mechanical energy can be generated by converting electrical energy using an electric motor. DC motors produce mechanical energy by converting DC power source [2]. The source of electrical energy uses a direct current power source. Mechanical force is generated based on the principle that a current-carrying conductor is in a magnetic field area, then the conductor experiences a mechanical force. The construction of a DC motor consists of a moving part or rotor and a stationary part or stator. There are five types of DC motors, namely separately excited DC motors, series DC motors, shunt DC motors, cumulative short compound DC motors, and cumulative long compound DC motors [1].

The characteristics of a DC motor are the relationship between armature torque, armature current, and armature speed. There are three characteristic relationships, namely 1) the characteristics between the armature torque and the armature current, 2) the characteristics of the armature speed and the armature current, and 3) the characteristics of the armature speed and the armature torque [1], [4]. The characteristics of a DC motor can be approximated by the following equation.

$$T_a \approx \emptyset . I_a$$
$$n \approx \frac{E_a}{\emptyset}$$

Ta	: armature torque
Ia	: armature current
n	: armature speed
Ea	: back of e.m.f.
Ø	: magnetic flux

2.1. Separately Excited DC Motor

The separately excited DC motor is a DC electric motor with a magnetic winding connected to another voltage source that is different from the voltage source for the armature. The equivalent circuit of separately excited DC motor is shown in Figure 1. Based on Figure 1, the mathematical equation is also obtained.
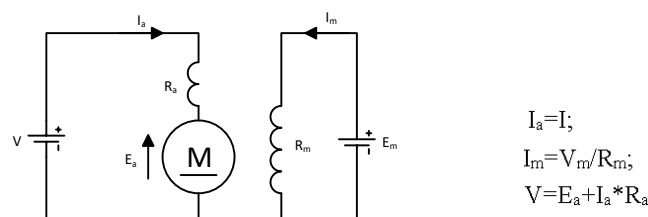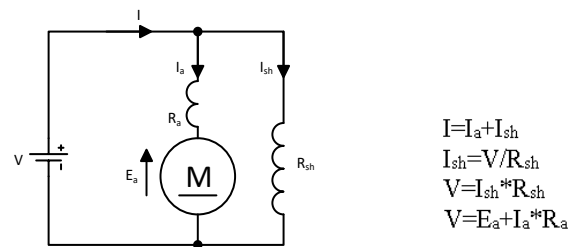

Figure 1. The equivalent circuit of separately excited DC motor [9].

The characteristics of a separately excited DC motor are identical to those of a shunt DC motor. Separately excited DC motors and shunt DC motors have a constant magnetic flux, so the characteristics of these two types of motors are identical. The discussion of the characteristics of a separately excited DC motor is presented in the discussion of the characteristics of a shunt DC motor.

2.2. Shunt DC Motor

The shunt DC motor is the same as a separately excited DC motor, except that the shunt winding is connected in parallel with the armature winding. The equivalent circuit of a DC shunt motor is shown in Figure 2. Based on Figure 2, the mathematical equation is also obtained.

$$I = I_a + I_{sh}$$
$$I_{sh} = V/R_{sh}$$
$$V = I_{sh}*R_{sh}$$
$$V = E_a + I_a*R_a$$

**Figure 2.** The equivalent circuit of shunt DC motor [9].

Figure 1 is the equivalent circuit of a separately excited DC motor, while Figure 2 is the equivalent circuit of a shunt DC motor. Separately excited DC motor and shunt DC motor have a constant field current when connected to a DC source which is also constant, so the magnetic flux produced is also constant.

The characteristics of the armature torque to the armature current *[Ta=f(Ia)]* form a straight line (linear), ignoring the armature reaction based on the equation $Ta = \emptyset * Ia$, because is constant, when the armature torque increases, the armature current also increases *(Ta≈Ia)*. The characteristics of separate excitation DC motors and shunt DC motors for the relationship between armature torque and armature current are shown in Figure 3. The 0-A area is the no-load current to generate the starting torque.
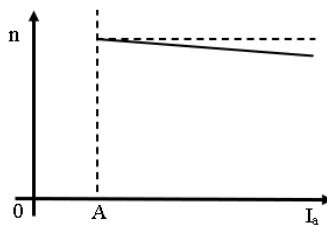
The characteristics of the armature speed to the armature current *[n=f(Ia)]* are based on $n = \frac{E_a}{\emptyset}$, if the motor load increases, the armature speed decreases, because *Ea=V-Ia*Ra*. The decrease in armature speed is also influenced by the armature resistance *(Ra)*, so that Ra is made small so that the power loss is also small, so that the decrease in speed due to an increase in load is also small.

The characteristics of a separate excitation DC motor and a shunt DC motor for the relationship between armature speed and armature current are shown in Figure 4.
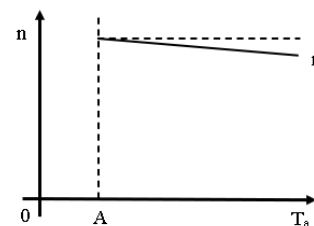
The characteristics of the armature speed to the armature torque *[n=f(Ta)]* form a linear curve. The magnetic flux is constant, so that the armature torque is proportional to the armature current *(Ta≈Ia)*. The characteristics of separate excitation DC motors and shunt DC motors for the relationship between armature speed and armature torque are shown in Figure 5.
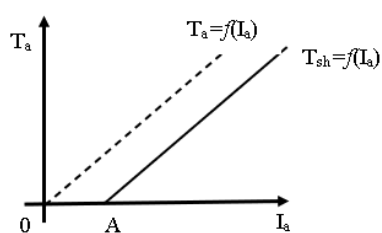
Figure 3. The characteristics between the armature torque and the armature current of the shunt DC motor [4].

Figure 4. The characteristics of the armature speed and the armature current of the shunt DC motor [4].

Figure 5. The characteristics of the armature speed and the armature torque of the shunt DC motor [4].

2.3. Series DC Motor

The series DC motor use series windings and connected in series with the armature windings. The equivalent circuit of a series DC motor is shown in Figure 6. Based on Figure 6, the mathematical equation is also obtained.

$$I=I_a=I_s$$
$$V=E_a+I_a*R_a+I_s*R_s$$
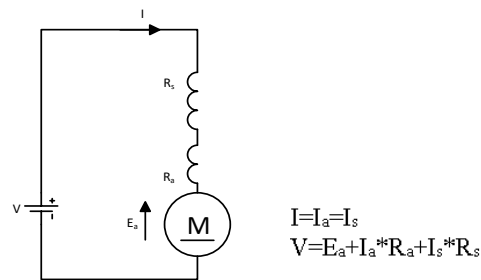
Figure 6. The equivalent circuit of series DC motor [9].

Figure 6 is the equivalent circuit of a series DC motor. The series field current is the same as the armature current, so when the armature current increases as the mechanical load increases, the series field current also increases *(I=Ia=Is)*.

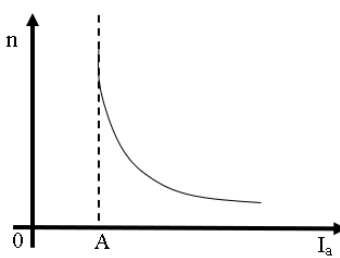The characteristics of the armature torque to the armature current *[Ta=f(Ia)]* form a curved line (quadratic) based on the equation *Ta=Ø*Ia*, because *Ø* is proportional to *Ia*, then *Ø=Ia*, so *Ta=Ia²*. Figure 7 shows the characteristic curve of the armature torque relationship to the armature current for a series DC motor. The 0-A area is the no-load current to generate the starting torque

The characteristics of the armature speed to the armature current are based on *n=Ea/Ø,* if the motor load increases, the armature current also increases, and the series field also increases, so the armature speed decreases drastically, because $n = \frac{V-I_a.R_a}{I_a}$. Figure 8 shows the characteristic curve of the relationship between armature speed and the armature current for series DC motor.

Series DC motor produce high torque at low speeds, while at high speeds the armature torque is low. High armature torque requires high armature current. The high armature current means the series field current is also high, so the series magnetic flux is also high. Based on the equations *Ta=Ø.Ia* and *n=Ea/Ø,* the characteristic curve of armature speed to armature torque *[n=f(Ta)]* is identical to the curve *[n=f(Ia)]*. Figure 9 shows the characteristic curve of the relationship between armature speed and the armature torque for series DC motor.
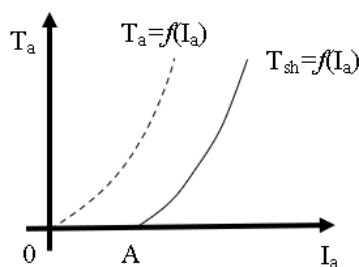
Figure 7. The characteristics between the armature torque and the armature current of the shunt DC motor [4].

Figure 8. The characteristics of the armature speed and the armature current of the shunt DC motor [4].
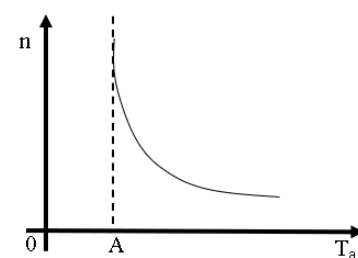
Figure 9. The characteristics of the armature speed and the armature torque of the shunt DC motor [4].

3. Experimental Setup and Simulink Models

Testing the characteristics of the DC motor is proven by running the DC motor on load. The DC generator is coupled to a DC motor as a load. By increasing the resistive load on the generator output voltage, the motor load also increases. For every increase in generator load, DC motor parameter data are recorded in the table including armature current, armature torque, and armature speed. Figure 10 shows the actual implementation of the characteristic test of a DC motor connected to a DC generator, while Figure 11 shows motor-generator shaft interconnection model using simulink. The generator

speed input is connected to the motor speed output, while the motor torque input is connected to the generator torque output. [10].
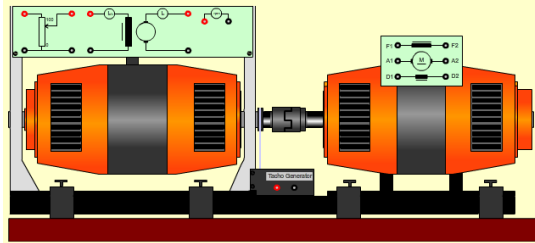

**Figure 10.** Motor-generator in real implementation.
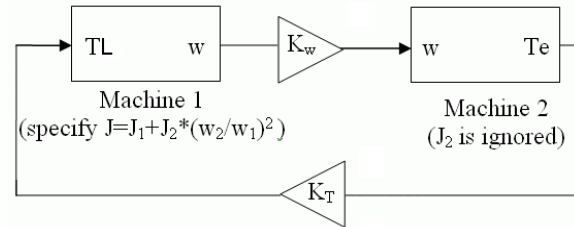
Figure 11. Model of motor-generator in virtual laboratory using Simulink [10].

3.1. Testing Separately Excited DC Motor

Implementation of a separately excited DC motor using Simulink is presented in Figure 12. Based on the actual implementation circuit in Figure 13, the characteristic test procedure can be implemented using Simulink. The separately excited DC motor requires two DC voltage sources, including fixed DC voltage source of 220V and variable DC voltage source of 0-220V. The fixed DC voltage source is to supply the field winding, while the variable voltage source is to supply the motor armature. Rheostat is needed to vary the field winding voltage to regulate the magnetic flux. The DC generator is coupled to a shaft with a DC motor. The DC generator is used as the load of the DC motor. When a DC motor rotates the DC generator, the DC generator generates a voltage which is connected to variable resistive load. By varying the resistance value of the resistive load variable, the generator output current increases, so that the generator torque also increases. The shaft coupling between the DC motor and the DC generator causes the torque generated to be the same between the two. With proper Simulink modeling, the output parameter of the DC motor model, the armature speed, is connected to the input speed of the DC generator model, and then the output parameter of the DC generator model, the armature torque, is fed back to the input of the DC motor model.
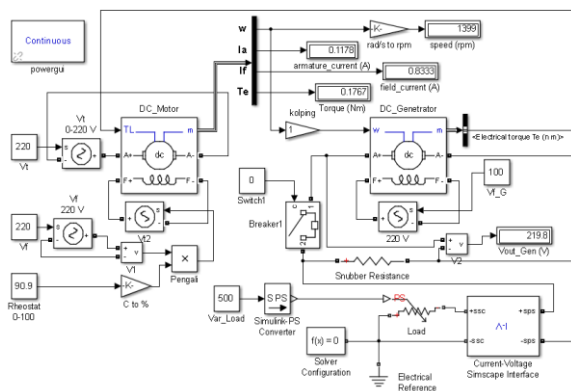
Figure 12. Simulink model for separately excited DC motor.
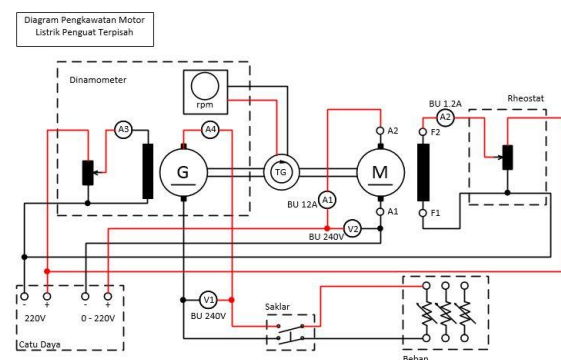
Figure 13. Circuit diagram for separately excited DC motor in actual implementation.

The process of running a DC motor can also be implemented on Simulink. With the feature of running an infinite simulation, starting the separately excited DC motor includes: 1) supplying the field winding so that a magnetic flux is generated in the DC motor, 2) supplying the DC motor armature gradually starting from 0V and slowly rising to a maximum limit of 220V, 3) adjusting the speed armature by varying the field winding voltage using a rheostat until the armature speed is 1400rpm no-load with an armature power supply of 220V.

The process of running a separately excited DC motor can also be implemented on Simulink. With the feature of running an infinite simulation, starting the DC motor includes: 1) supplying the field

winding so that a magnetic flux is generated in the DC motor, 2) supplying the DC motor armature gradually starting from 0V and slowly rising to a maximum limit of 220V, 3) adjusting the speed armature by varying the field winding voltage using a rheostat until the armature speed is 1400rpm no-load with an armature power supply of 220V.

Starting from the no-load condition, the DC motor is loaded by adjusting the variable resistive load on the DC generator until the appropriate DC motor armature current is obtained. Every time the load increases on the DC generator, a step is made to increase the DC motor armature current of 0.5A then record each parameter including the armature speed and armature speed. Data collection is limited until the maximum armature current value is 5A.
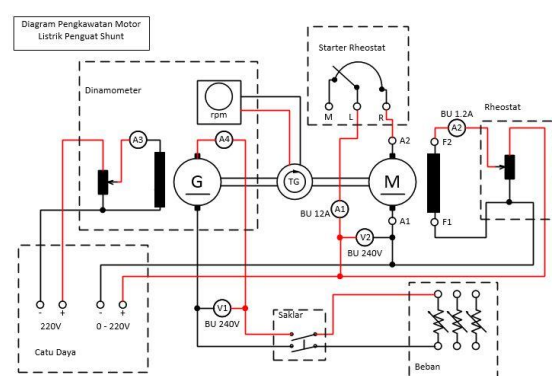
3.2. Testing of Shunt DC Motor

Implementation of a shunt DC motor using Simulink is presented in Figure 14. Based on the actual implementation circuit in Figure 15, the characteristic test procedure can be implemented using Simulink. Unlike the separately excited DC motor, the shunt DC motor only needs one type of DC voltage source, namely a 0-220V variable DC voltage source. The power supply for the field winding is taken from the DC motor armature power supply. Rheostats are also needed in shunt DC motors to vary the field winding voltage to regulate the magnetic flux. There is an additional tool, namely a motor starter which is used to provide a 0-220V variable power supply pause to generate magnetic flux. Just as in the separately excited DC motor test, the DC generator is coupled to the shaft with a shunt DC motor.

The process of running a shunt DC motor can also be implemented on Simulink. In the same way, running the simulation feature indefinitely, starting the shunt DC motor includes: 1) initial conditions, the motor starter device is in an off or stop condition, the field winding rheostat is in 100% condition, 2) supplying the field winding using a variable power supply up to a maximum voltage of 220V so that the magnetic flux is generated in the DC motor, 3) supplying the motor armature by turning the motor starter from the stop condition to the run condition, so that the armature rotates, 3) adjusting the speed of the armature by varying the field winding voltage using a rheostat until the armature speed is 1400rpm no-load with 220V armature power supply.

The same steps are also carried out in testing the shunt DC motor, starting from the no-load condition, the DC motor is loaded by adjusting the variable resistive load on the DC generator until the appropriate DC motor armature current is obtained. Every time the load increases on the DC generator, a step is made to increase the DC motor armature current by 0.5A then record each parameter including the armature speed and armature speed. Data collection is limited until the maximum armature current value is 5A.
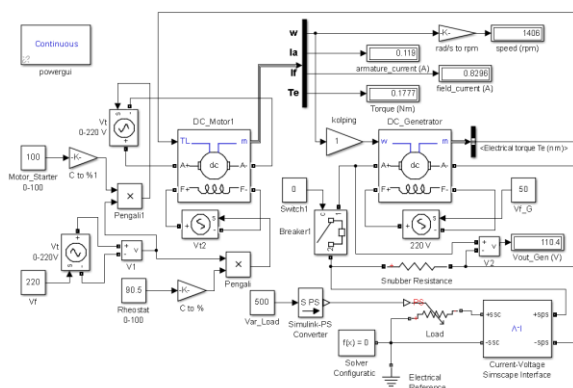
Figure 14. Simulink model for shunt DC motor.

Figure 15. Circuit diagram for shunt DC motor in actual implementation.
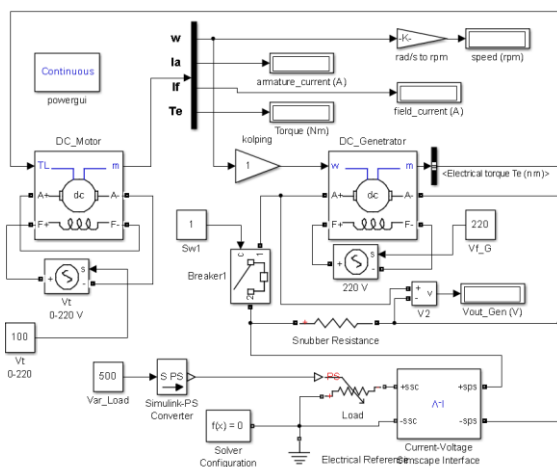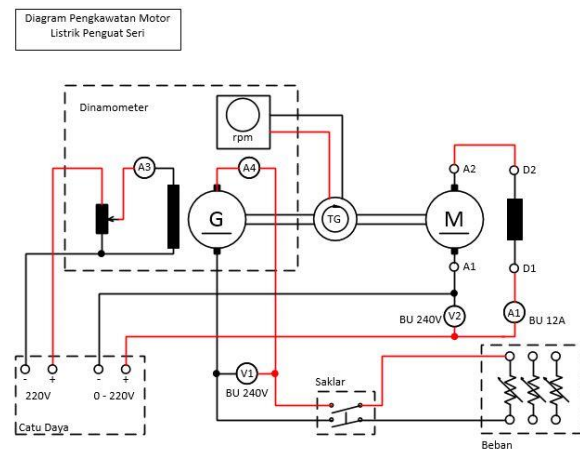
3.3. Testing of Series DC Motor

Implementation of series DC motor using Simulink is presented in Figure 16. Based on the actual implementation circuit in Figure 17, the characteristic test procedure can be implemented using Simulink. Series DC motors must run with on-load because if run with no-load, the armature speed will be very high. This is because when the series DC motor is run at no-load condition, the armature current is very small, because the field winding is connected in series with the armature; the magnetic flux produced is also small so the armature speed will be very high. Adjusting the armature speed on a series DC motor is very difficult, so this type of series DC motor is avoided for purposes that require a relatively constant armature speed. The series DC motor produces high torque at low armature speeds, so that at high load increases, the series DC motor has a stronger torque.

The process of running a series DC motor can also be implemented on Simulink. In the same way, using the unlimited simulation feature, starting a series DC motor includes: 1) in the initial state, the DC generator is already in a loaded condition, meaning that the breaker leading to the variable resistive load is in the on condition and the field winding power supply on the DC generator is on. , 2) supplying the motor armature gradually starting from 0V and slowly rising to the maximum limit of 220V, 3) it is very difficult to get the desired armature speed, it can be obtained by adjusting the variable resistive load on the generator so that the motor armature speed is 1400rpm at the armature supply voltage 220V DC motor.

Starting at the on-load condition, the armature speed is 1400rpm, in the same way in the previous test, the load is increased until the appropriate DC motor armature current is obtained. Every time the load increases on the DC generator, a step is made to increase the DC motor armature current by 0.5A then record each parameter including the armature speed and armature speed. Data collection is limited until the maximum armature current value is 5A.

Figure 16. Simulink model for series DC motor.

Figure 17. Circuit diagram for series DC motor in actual implementation.

4. Result and Discussion

The results of testing the characteristics of a DC motor based on the Simulink simulation model for separate, shunt, and series excitation DC motors are shown in Table x. Each test data includes armature current, armature speed, and armature torque as data to graph the characteristics of each type of DC motor.

Based on the data in Table 1, a graph of the characteristics of each DC motor can be made, including the characteristics of armature torque to armature current [Ta=f(Ia)], characteristics of armature speed to armature current [n=f(Ia)], and characteristics of armature speed to armature torque [n=f(Ta)]. The characteristics of a separate excitation DC motor are shown in Figure 18, the characteristics of a shunt DC motor are shown in Figure 19, and the characteristics of a series DC motor are shown in Figure 20.

Table 1. The results of the simulation of testing the characteristics of a DC motor.

Separately Excited			Shunt			Series		
Ia (A)	N (rpm)	Ta (Nm)	Ia (A)	N (rpm)	Ta (Nm)	Ia (A)	N (rpm)	Ta (Nm)
1,032	1397	1,535	1,021	1396	1,533	0,830	1400	1,242
1,536	1395	2,304	1,533	1394	2,301	1,605	721,2	4,637
2,056	1394	3,084	2,006	1392	3,011	2,070	557,7	7,714
2,546	1392	3,819	2,541	1390	3,815	2,506	460	11,303
3,031	1390	4,547	3,025	1388	4,542	3,005	382	16,253
3,497	1388	5,246	3,551	1386	5,329	3,503	327	22,01
3,995	1386	5,993	4,052	1384	6,083	4,003	285	28,845
4,525	1384	6,787	4,585	1382	6,883	4,506	253	36,554
5,015	1382	7,522	5,149	1380	7,731	5,003	227	45,06

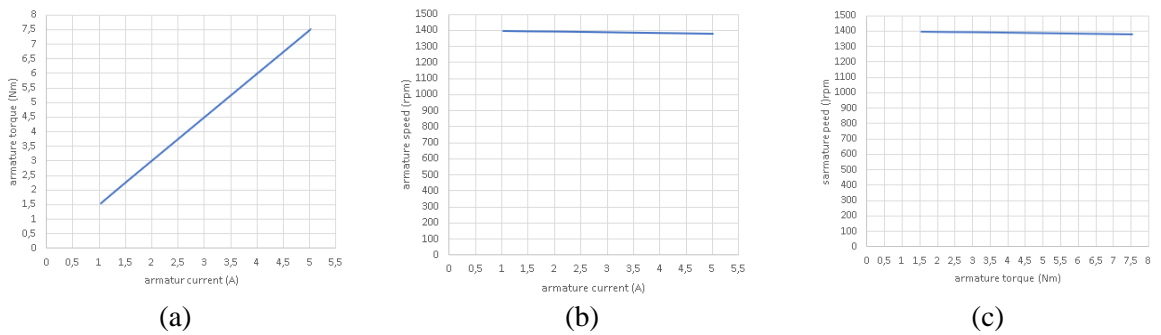(a)   (b)   (c)

Figure 18. Separately excited DC motor characteristics graph, (a) Ta=f(Ia), (b) n=f(Ia), (c) n=f(Ta).

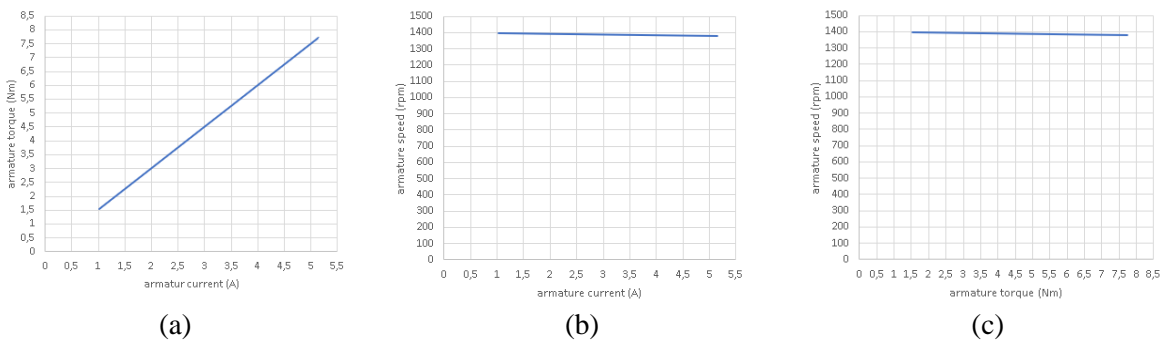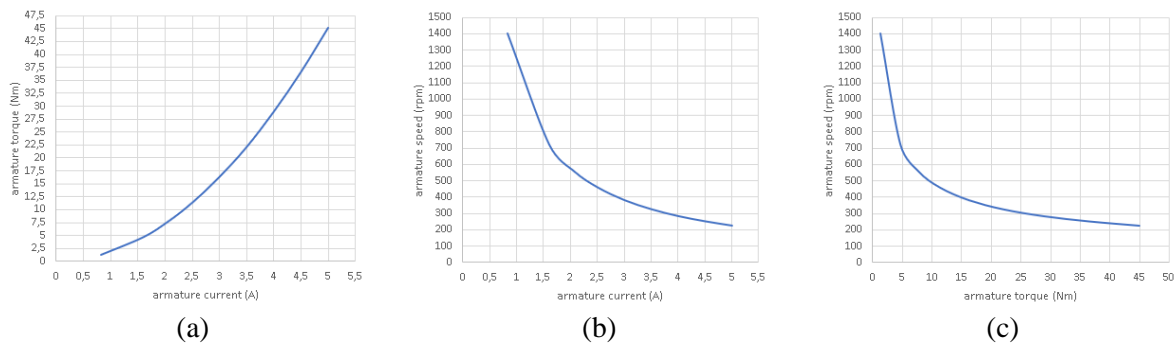(a)   (b)   (c)

Figure 19. Shunt DC motor characteristics graph, (a) Ta=f(Ia), (b) n=f(Ia), (c) n=f(Ta).

Figure 20. Series DC motor characteristics graph, (a) Ta=f(Ia), (b) n=f(Ia), (c) n=f(Ta).

Based on the test data, the DC motor is run from zero rpm to 1400rpm without load on a 220V voltage source. Except for the series DC motor, it runs from zero rpm to 220V under load. We know that a series DC motor should not be run under no-load condition, because the armature speed will be very high. Testing data retrieval starts from the no-load condition. Variations in the load on the generator by manipulating the resistive load variable cause an increase in the load on the DC motor so that the armature current also increases. The load variation is made in 0.5A increments of the motor armature current until an armature current of 5A is obtained. Every change in load increase or increase in armature current, data of armature speed and armature torque are recorded, so that three data are obtained at one time of increasing load, including armature current, armature speed, and armature torque.

The data that has been obtained on each type of DC motor, then graphed the characteristics of the relationship between armature torque and armature current, armature speed to armature current, and armature speed to armature torque. Three kinds of characteristics for each type of motor have been obtained and are in accordance with the theory discussed earlier. Thus, testing the characteristics of a DC motor coupled with a DC generator has been successful. Similar models can be used for testing other types of electrical machines such as DC generators, induction motors, synchronous motors, and synchronous generators.

5. Conclusion
In this study, testing the characteristics of a DC motor coupled with a DC generator as a load has been completed. The testing process is carried out by infinitely simulating so that the DC motor starting process starts from zero rpm to a no-load speed of 1400 rpm at a source voltage of 220V. From no-load conditions and variations in load increases, data on changes related to armature current, armature speed, and armature torque have been obtained. The graph of the characteristics of all types of DC motors results from the test is very in line with the theory.

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