Design of Software Laboratory Teaching Tool for DC Machine Experiments Using MATLAB / Simulink

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Abstract

A DC machine has to be tested using MATLAB software simulation for proper fabrication and trouble free operation. From the tests, one can determine the external characteristics needed for application of these machines. In addition, one can find the efficiency, rating and temperature rise of the machine. The current paper suggests simulation models representing developed DC machine experiments in an effort to design a computational laboratory to support and enhance undergraduate electrical machine courses at electrical engineering departments in Iraqi Universities.
Key-words: DC machines, tests, software laboratory, MATLAB/Simulink.

الخلاصة

تمّ اختبار ماكنة التيار المستمر عن طريق المحاكاة باستخدام برنامج MATLAB لأغراض التصنيع الصحيح لتلك الماكنة والتشغيل الخالي من المشاكل. هذه الاختبارات تساعد على تحديد الخصائص الخارجية المتطلبة لتطبيقات هذه المكائن. بالإضافة إلى إنها تمّكننا من إيجاد الكفاءة والقيم المقررة وارتفاع درجة حرارة الماكنة. يقترح البحث الحالي نماذج محاكاة تمثل تطويراً لتجارب مختبريه لمكائن التيار المستمر في جهود لتصميم مختبر حاسوبي لدعم وتعزيز المُقرّر التعليمي لمادة المكائن الكهربائية لطلبة الدراسات الأولية في أقسام الهندسة الكهربائية في جامعات العراق.

1. Introduction

During the last years, software tools in various forms have started playing an increasingly important role in educating students of engineering subjects like electrical, mechanical or civil engineering.

MATLAB and companion products offer an array of tools for simulation and modeling. These tools have been extensively used to support and enhance electric machinery courses. MATLAB with its toolboxes such as Simulink [*Simulink* 2000] and SimPowerSystems [*Mathworks* 2001] is one of the most popular software packages used by educators to enhance teaching the characteristics of electric machines [*Li* 2006, *Durán* 2007, and *Ong*, 1998]. Simulink models for transformer and induction motor experiments and successfully integrated them into an undergraduate electric machinery course was presented in [*S. Ayasun* 2005, and 2006]. In order to have a complete set of simulation tools for electric machinery experiments, the previously designed software laboratory [*S. Ayasun* 2005, and 2006] should be extended to include experiments of DC motors.

In an effort to restructure and modernize electric machinery courses at electrical engineering departments in Iraqi Universities, authors have developed Simulink models for DC machine experiments to be successfully integrated them into an undergraduate electric machinery course. The authors have been suggested designing a software laboratory to incorporate the simulation models into the laboratory section of the course. The objective of this paper is to present simulation models of DC machine experiments in an effort to design a software laboratory. These models include Simulink models of some tests such as open circuit tests, load and no load tests.

Experimental tests are performed to obtain the characteristics of the machines in the lab and to obtain parameters for modeling the machines. Open circuit tests, load and no load tests will be modeled similar to obtain the required parameters of the machine.

The proposed simulation models are introduced to offer students all simulation models in a single and easy-to-use software package. The simulation models of DC motors are integrated into a senior level electric machinery course to enhance the teaching the tests of the DC machines. The enhancement is achieved by using the simulation models for various educational activities such as classroom demonstration, exercises, and assignments. It has been observed that with the help of simulation results they obtain, students increase their understanding of DC machine external characteristics as well as determining the efficiency, rating and temperature rise of the machine beyond the understanding they gain from classroom lectures and textbooks. Some of the tests are discussed in sequence below.

2. Machine Tests:

2.1 Machine Resistance Test:

Measurement of winding resistances of field windings and armature winding are performed by *V-I* method. Even though any value of applied voltage can be used, the highest permissible voltage/current is chosen during the test to minimize the errors.

2.1.1 Measurement of Armature Resistance:

The field is not excited during this test. The armature circuit consists of two resistances in series. They are armature winding resistance and resistance due to the brushes and the brush drop. The brush contact drop behaves like a non-linear resistance. To separate this from the armature circuit resistance and brush resistance, a number of *V-I* readings are taken. For large values of current, the equivalent armature resistance R_a is taken to be V/I ohm. If the value of brush drop can be neglected then the armature resistance is $R_a=V_a/I_a$ ohm as shown in Fig. 1(a), where V_a and I_a are the armature voltage and current, respectively.

2.1.2 Measurement of Field Resistance:

This test determines the field winding resistance R_f. The input voltage is set to zero during this test. By using adjustable field resistance R_{adj} as shown in Fig. 1(b), the readings of field voltage V_f and current I_f can be used to determine R_f as: $R_f = V_f / I_f$.

2.2 Open Circuit Voltage Characteristic (OCC) Test:

The OCC is a graph showing the variation of the induced electro motive force *emf* as a function of field (excitation) current I_f, when the speed ω is held constant, with the load current being zero. A plot of the open circuit voltage E versus the I_f will exhibit the same characteristics shown in the flux Φ versus current I_f graph. Thus, E can be described as [*S. J. Chapman* 2004]:

$$E = K \omega \Phi = K_e I_f \qquad \text{for constant speed} \qquad (1)$$

, where $I_f = K_f \Phi$ and K, K_e, and K_f are constants.

The OCC is experimentally determined by running the machine as a separately excited generator on no-load at a constant speed and noting the terminal voltage as a function of field current. This curve can be used to find the OCC at other speeds and also the self-excited voltage when the machine works as a shunt generator [*Vasudevan* 2007, and *Ougrinovski* 2004].

The voltage buildup in a DC shunt generator depends on the presence of a *residual flux* Φ_{res} in the poles of the generator.

At no load, I_f is the only current caused by the induced voltage E. This current produces an *mmf* in the poles, which increases Φ in them. The increase in Φ causes an increase in E and so on [*V. Ougrinovski* 2001].

2.3 Short Circuit Characteristics (SCC) Test:

In this test, the armature is kept short circuited through an ammeter. The machine is demagnetized and an extremely small field current is passed through the field. The variation of the short circuit current as a function of field current is plotted as the SCC. The speed is to be held constant during this test also. The SCC test gives an idea of the armature drop at any load current [*Vasudevan* 2007].

2.4 Locked Rotor Test:

This test determines the armature resistance R_a of the DC motor. The input voltage is adjusted to get the rated motor armature current during this test. The terminal voltage V_t and armature current I_a values obtained during this test are used to determine the armature resistance as follows: $R_a = V_t / I_a$.

2.5 Load Characteristic Test:

To assess the rating of a machine, a load test has to be conducted. The load test gives the information about the efficiency of a given machine at any load condition. Also, it gives the temperature rise of the machine. If the temperature rise is below the permissible value for the insulation then the machine can be safely operated at that load, else the load has to be reduced. The maximum continuous load that can be delivered by the machine without exceeding the temperature rise for the insulation used is termed as the continuous rating of the machine. Thus, the load test alone can give us the proper information of the rating and also can help in the direct measurement of the efficiency [*Vasudevan* 2007].

2.6 Measurement of Rotor Inertia (Retardation Test):

The moment of inertia J value is very important for the selection of a proper motor for drives involving many starts and stops or requiring very good speed control characteristics.

The inertia can be determined by a retardation test. This test works on the principle that when a motor is switched off from the mains it decelerates and comes to rest. In this test, the motor speed is taken to some high value. The angular retardation $d\omega/dt$ at any speed ω is proportional to the retarding torque and is inversely proportional to the inertia. The torque lost at any speed is calculated by running the motor at that speed steadily on no load and noticing the power input. From this power, the losses that take place in the armature and field are deducted to get the power converted into mechanical form. All this power is spent in overcoming the mechanical losses P_{rot} at that speed. This can be repeated at any defined speed to get the lost power and torque lost due to mechanical losses.

The torque required by the losses is supplied by the energy stored in the motor inertia. The lost torque T_{lost} at any speed ω can be written as:

$$T_{lost} = P_{rot} / \omega = J\, d\omega/dt \quad (2)$$

Here, the $d\omega/dt$ is the slope of the retardation curve and the T_{lost} is the torque required to be met at the given speed. From these values the moment of inertia can be computed as [*KFUPM* 2005]:

$$J = \frac{T_{lost}}{d\omega / dt} = \frac{P_{rot}}{\omega . d\omega / dt} \quad kg.m^2 \quad (3)$$

2.7 Efficiency of a DC Machine:

A machine when loaded yields an output. The input to the machine is measured at that operating point. The efficiency η in per unit is given as the ratio of output power P_{out} to input power P_{in}.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + \sum losses} = \frac{P_{in} - \sum losses}{P_{in}} = \frac{VI - \sum losses}{VI} \quad (4)$$

, where $\sum losses$ is the total power lost inside the machine, and V and I are the terminal voltage and input current, respectively [*Vasudevan* 2007].

3. MATLAB/Simulink Models of Testing:

This software simulation illustrates principles of electric machinery and familiarizes students with fundamentals of DC machines. The students will learn about the characteristics of DC machines including no-load and load characteristics.

A DC motor block of SimPowerSystems toolbox is used. The DC machine block shown in Fig. 2, implements a separately excited DC machine. An access is provided to the field connections (*F*+, *F*-) so that the machine model can be used as a shunt-connected.

The field circuit which is represented by an inductor L_f and series resistor R_f is connected between the ports (*F*+, *F*-). The armature circuit consists of an inductor L_a and resistor R_a in series with an electromotive force E and is connected between the ports (*A*+, *A*-). The load torque is specified by the input port T_L.

The electrical and mechanical parameters of the motor could be specified using its dialog box. Observe that 220V DC source is applied to the armature and field circuits. An external resistance R_{adj} is inserted in series with the field circuit to realize the field resistance speed control.

The output port (port *m*) allows for the measurement of several variables, such as rotor speed, armature and field currents, and electromechanical torque developed by the motor. Through the scope and display block, the waveform and steady-state value of the rotor speed can be easily measured in radian per second (*r*/*s*), or the corresponding data can be written to MAT Lab's workspace using the data box to make use of other graphical tools available in MATLAB.

4. Using the Proposed Models in the Educational Field:

This section describes how the proposed Simulink models can be used in a senior level machinery course (Electric Machinery 1) at Departments of Electrical Engineering in Iraqi universities. This course is a DC machines course that offers the steady-state operation principles and mathematical models of DC machines.

The topics covered by the course are the structure of DC machines, per-phase equivalent circuit model, torque-speed characteristic, and speed control methods.

After the steady-state equivalent circuit model, operation principles, load and no-load characteristics are covered in the class, the instructor uses Simulink models of the machine tests to demonstrate the effects of equivalent circuit parameters on the motor performance under a wide range of loading conditions. After the demonstration, students are asked to obtain the load and no-load characteristics and compare them with the theoretical results learned from the lecture. Students through this exercise should have a basic understanding of the steady-operation of DC machines and the all the necessary tests. Moreover, after having enough experiences with the simulation models, the following exercises are assigned to students:

* Obtain the plot of E vs. I_f at no load and compare this result with the hardware experiment.
* Calculate the machines winding resistances R_a and R_f.
* Obtain the plot of Speed N vs. input current I_{in}, N vs. Torque T, P_{out} vs. I_{in}, N vs. P_{out}, η vs. T, and η vs. I_{in} for a DC motor and then compare the above plots with hardware experimental results.
* For the plot of η vs. I_{in}, compare the rated value of I_{in} with its value at maximum efficiency (η_{max}) point.
* Determine the Speed Regulation SR of the proposed DC motor and explain how the speed is changed and why the change in speed occurs.
* Obtain the plot of P_{rot} vs. V_{in} at N = 1500 rpm and then repeat the test with some other speeds.
* Obtain the plot of the rotor deceleration $d\omega/dt$ vs. no-load speed as the motor is switched off from the main and calculate the corresponding moment of inertia.
* Obtain the plot of the load characteristic for the proposed DC generator and determine the Voltage Regulation VR.

5. Simulation Results and Discussion:

Each electric machine is designed by a manufacturer to operate in a certain range of voltages and currents. The parameters quoted by the manufacturer are known as rating of the machine. Since the Simulink simulation programs are designed based on the real machine in the power lab, the following ratings are used: Power; 4HP, voltage; 220V, current; 15.4A, speed; 1500rpm, and field current; 0.6748A. The equivalent circuit parameters of the motor are: R_f =326Ω, L_f =5.46mH, R_a=2Ω, and L_a=16.2mH, J=0.05$kg.m^2$.

This section presents simulation results for the necessary tests of the DC machines. All the required curves obtained form the tests are determined using the MATLAB/Simulink models presented in the following sections.

5.1 OCC Test:

The open-circuit voltage characteristic *OCC* of the separately excited DC machines is demonstrated in this test as illustrated in Fig. 3. This test examines the relationship between the generated voltage E and excitation current I_f of a generator at no load; $E = f(I_f)$. I_f can be adjusted through adjustable resistance (rheostat or potentiometer) R_{adj}. The voltage applied to the field circuit V_f is kept constant at its nominal value 220V. Through the scope and display block, the voltage and current waveforms can be seen. The voltage and current values can also be obtained through *Display E* and *Display* I_f, respectively. In this test, the speed of the generator shaft must be constant.

I_f can be adjusted by changing V_f and R_{adj}. By varying I_f in the steps from 0 to ~120 % of its rated value, the open circuit generator terminal voltage E against I_f can be plotted as in Fig. 4. In order to obtain zero value of I_f, V_f may be set to zero. It should be noted that during the test, it is not important what speed you use as long as it is kept constant. The machines in the laboratory are safe up to 120% of their rated rpm. It should be noted that E starts from a nonzero value.

By varying the generator shaft speed to 120% and 80% of the rated value, it can observe how fast I_f and E are developed compared to the previous step.
It can be seen that increasing the speed causes increasing E and vise versa. It can also be seen that, there is small amount of induced voltage E in spite of nonexistence of any field current I_f because of presence of the *residual flux* in the poles of the generator.

5.2 Machine Resistance Test

This test determines the field and armature winding resistances. In the field circuit, a resistor R_{adj} is connected in series with the field winding to control I_f as shown in Fig. 5. In this test, the field voltage V_f is set to its nominal value 220V. It must make sure that the input voltage V_{in} is set to 0V. I_f and V_f values can be recorded as in Table (1). The test must be repeated at least three times with different values of R_{adj}.

The field resistance R_f can be found from $R_f = V_f / I_f$. The averaged value of three values of $R_f \approx 326\ \Omega$.

For finding the armature resistance R_a, the simulations are performed using the model shown in Fig. 6. The voltage and current in the armature circuit must be used to find R_a. First, the nominal value V_{in} is kept constant to 220V and make sure that V_f is set to 0V. In this test, the load torque T_L is set to small value i.e. 0.1 or 0.01 N-m. The values of V_t and I_{in} can be recorded as in Table 1.
The readings must be repeated with three different values of R_{adj}. Therefore, R_a can be found from $R_a = V_t / I_{in}$ and its averaged value $\approx 2\ \Omega$.

5.3 Machine Loss Test

In this test, rotational loss P_{rot} of the machine can be determined. This power loss can be calculated from the following equation [*S. J. Chapman* 2004]:

$$P_{rot} = P_{in} - R_a I_a^2 + R_f I_f^2 \quad (5)$$

By recalling that R_a and R_f were obtained in the previous section and using the Fig. 7 for measuring the values P_{in}, I_a, and I_f , P_{rot} can be estimated. In this test, first setting V_{in} to 220V and making sure that no load torque remains fixed on 0.6 N-m and the speed N must be constant. By measuring P_{in}, I_f, and I_a, Table 2 can be obtained.

P_{rot} can be calculated from the Eq. 5. For later computations, it would be desirable to have a family of curves for the P_{rot} as a function of V_{in} at certain speeds N.
The machine loss tests for different speeds are done to get the results shown in Fig. 8. Fig. 9 shows the 3-D plot of the rotational losses P_{rot} as a function of input voltage V_{in} and speed N. The dotted line represents the P_{rot} as a function of both variables V_{in} and N.

5.4 SCC Test:

This test gives an idea of the armature drop V_a at any short circuit load current I_{sc}.

I_f, extremely, small field current. Therefore, $I_{sc} \approx I_a$. The DC machine in this test is connected as a separately excited DC generator as shown in Fig. 10. The variation of I_{sc} as a function of I_f for three different speeds is plotted as the short circuit characteristics as shown in Fig. 11. The figure shows that the curve with higher speed has higher I_{sc} values.

Fig. 12 gives an idea of the armature drop V_a at any load current from the no-load to about 120% of full load.

5.5 Locked Rotor Test:

The machine in this test is used as self-excited shunt DC motor. With rotor locked ($N = 0$), the motor power supply V_{in} must be adjusted until the motor armature current equal the rated value I_{ar}=14.72A.

The values of T_e (developed torque), I_a, and V_{in} may be recorded as in the Table 3.

The values of I_a and V_{in} obtained by running the circuit in the Fig. 13, help us to determine the armature resistance R_a, where $R_a=V_{in}/I_a = 29.44/14.72 = 2\Omega$.

P_{in} in the table represents the short circuit input power P_{sc}, which also can be determined as follows; $P_{sc}=I_a^2R_a+I_f^2R_f$ $=14.72^2*2+0.09031^2*326=436.016$W. T_e also represents the short circuit developed torque T_{sc}. Each of P_{sc} and T_{sc} acts about 13 % of the corresponding rated values.

5.6 Measurement of Rotor Inertia:

It is done at no-load. V_{in} is kept constant at nominal value 220V. To find the moment of rotor inertia J, simulations are performed using the model shown in Fig. 14 for seven values of speed as shown in the Table 4. The values of currents and power are recorded; therefore, P_{rot} can be calculated according to Eq. 5. The deceleration $d\omega/dt$ is measured at the moment the motor is switched off from the supply. The values of J can be determined using the Eq. 3. The average value of the rotor moment of inertia; $J_{av}= (\sum J)/7 \approx 0.05$ $kg.m^2$.

Fig. 15 shows the variation of P_{rot} with the machine speed N for constant input voltage. It should be noted that increasing of N causes increasing of P_{rot}. Also it can be seen form Fig. 16 that the input current I_{in} increases with N increase, since increasing of N causes increasing of the *emf*, which causes increasing of current.
The direct proportion of the retarding torque T_{lost} vs. N can be shown in Fig. 17. Fig. 18 shows the inverse proportion relationship between the retardation (or deceleration) of the motor and its initial no-load speed.

5.7 Load Characteristic Test of a Shunt Excited DC Motor:

In a shunt motor, as the field winding is connected across the supply terminals, the field current is independent of the load conditions. As a result, the flux for a shunt motor can be considered constant and independent of the armature current, therefore, the only effect the load can have on the speed is to increase the effect of the voltage drop in the armature. The equations that describe load characteristics of a shunt motor can be found as:

$$\omega = \frac{E}{K\Phi} = \frac{V_t - I_a R_a}{K\Phi} = \frac{V_t}{K\Phi} - \frac{I_a R_a}{(K\Phi)^2} T_e \qquad (6)$$

, where: ω: is motor speed (r/s), K: is a constant that includes the winding and structural details of the motor, Φ: is the induced flux per pole (Wb), and T_e: is induced torque (N-m).

The Speed Regulation *SR* of the motor can be as the change in speed when the load on the motor is reduced from the rated value to no-load value as follows:

$$\%SR = (N_{NL} - N_{FL}) / N_{FL} \times 100 \qquad (7)$$

The characteristics of speed vs. input current and speed vs. induced torque can be obtained using the diagram shown in Fig. 19. In this diagram, I_f can be changed through R_{adj}.

First, the nominal value of V_{in} is set to 220V and the load torque T_L must be in the range (0.6-27) N-m. The following data: T_L, I_{in}, V_{in}, P_{in}, I_f, and N (rpm) have been read. Noticing that the input current I_{in} can be adjusted via T_L and the minimum value of I_{in} as $I_{in\ min}$ is reading at minimum T_L (0.6 Nm). By varying T_L in order to adjust the I_{in} from $I_{in\ min}$ to about 160% of its rated value in increments of 1A, the entire corresponding load characteristics of the DC motor is illustrated as in the Fig. 20. This figure consists of some curves such as the plot curves; N vs. I_{in}, N vs. T, P_{out} vs. I_{in}, N vs. P_{out}, η vs. I_{in}, and η vs. T.

The inverse proportion for each of the torque and the input current with speed can be seen in Fig. 20(a). This figure represents the typical speed vs. load (torque or current) characteristics for shunt-excited DC motor.

The drop in the speed N is resulting from the armature voltage drop according to the Eq. 6. The speed regulation for the motor from the full load current 15.4A to the no-load current 4.057A is equal to 11.8%. Fig. 20(b) shows output power as a function of the input current I_{in}. The input power P_{in} and output power P_{out} are inversely proportion with N as shown in Fig. 20(c), while Fig. 20(d) illustrates the efficiency η as a function of T or I_{in}.

It should be noted that P_{out} and then η can be calculated using; $P_{out}=\omega T_e$ and $\eta=P_{out}/P_{in}$.

From the η vs. current curve in Fig. 20(d), it can be seen that the maximum efficiency η_{max} is happening at I_{in}=19.6A which acts as 1.27273 times the rated current.

This current also can be found mathematically using the following equation: I_a (at η_{max}) = $(P_C/R_a)^{1/2}$, where the constant losses $P_C=P_{rot}$ (at η_{max})$+I_f^2R_f$ [*K. Vasudevan* 2007] , and by using the data in the Tables: P_C=540.015+0.6748^2*326=688.4607W. Therefore, the armature current at η_{max} is I_a=18.553A and I_{in}=19.22825 A, which is equal to 1.24859 times the rated current.

The difference exists between the two values is because of neglecting some losses such as brush loss, commutating pole and compensating winding losses and the stray losses. Table 5 illustrates the values of η at the cases; no-load, load, and maximum efficiency η_{max}.

It can be seen from the Table 2 that P_{rot} at rated speed is 586.8473W, and from the Table 5, the rated output power $P_{out}=P_{inrated}*\eta_{rated}$=3388*0.6834=2315.2, therefore, the rotational losses will approximate 25 % of the rated power. This value is high, and it can be reduced by reducing the field resistance.

5.8 Terminal Voltage (Load) Characteristics Test for a Separately Excited DC Generator:

The terminal voltage characteristic; $V_t = f\ (I_L)$ of a generator describes the voltage across the DC generator's terminals versus the load (armature) current when the generator is converting power. This characteristic can be obtained by running the circuit shown in Fig. 21.

The terminal voltage V_t of a separately excited generator decreases slightly with an increase in the load current, mainly because of the voltage drop in the armature resistance as shown in Fig. 22. It should be noted that the internal characteristic curve E can obtained from the external one by adding the V_t curve in Fig. 22 to the armature drop $V_a(=I_aR_a)$ for each value of load current, whereas, $E = V_t + V_a$.

The Voltage Regulation VR of the generator is found by determining the change of its terminal voltage from the no-load to the full load with the change in load current as:

$$\%VR = (V_{NL} - V_{FL})/V_{FL} \times 100 \qquad (8)$$

For the generator proposed in the diagram shown in Fig. 21, the VR=15.82%.

6. Conclusions

The paper presents a laboratory development and restructuring based upon an integrative teaching approach and structure for the course of DC electric machines at electric engineering departments in Iraqi universities.

The teaching of fundamentals of DC machines has been enhanced using the proposed simulation models.

Simulation models of DC machine tests have been developed using MATLAB/Simulink. It has been shown that proposed simulation models correctly predict the values of the DC machine parameters and the characteristics of DC machines. Furthermore, the proposed Simulink models can be successfully integrated into an electric machinery course as a part of the software laboratory.

The paper demonstrates laboratory experiments developed for testing the DC machines, making students to be able to gain hands-on experience for steady-state operation, fundamentals, and characteristics of DC machines, providing them a complete view of a testing of DC machines. It illustrates how MATLAB/Simulink is used in the laboratory experiments and how to let students quickly familiar with integrated DC machines laboratory systems, and MATLAB/Simulink.

Future work will involve further development of simulation models to include the dynamic response for the DC machines.

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Table 1: Calculation of Field and Armature Resistances

I_f (A)	V_f (V)	$R_f = V_f / I_f$ (Ω)	I_{in} (A)	V_t (V)	$R_a = V_t / I_{in}$ (Ω)
0.4622	150.7	326.0493	44	88	2
0.5164	168.4	326.1038	55	110	2
0.5851	190.7	325.9272	73.33	146.7	2.0005
Average		326			2

Table 2: Calculation of Rotational Losses

Case	N_r (rpm)	I_f (A)	I_a (A)	P_{in} (W)	P_{rot} (W)
No-load	1677	0.6748	3.385	893.1	721.7256
Full-load	1500	0.7591	2.735	768.8	586.8473
Max. Efficiency	1433	0.796	2.511	727.6	540.061

Table 3: Calculation of Motor Armature Resistance using Locked Rotor Test

I_a (A)	I_f (A)	V_{in} (V)	I_{in} (A)	P_{in} (W)	T_e (N-m)
14.72	0.09031	29.44	14.81	436	2.353

Table 4: Calculation of Rotor Moment of Inertia for Different Speeds

N_r (rpm)	I_f (A)	I_a (A)	P_{in} (W)	P_{rot} (W)	$d\omega/dt$ (r/s^2)	$J(kg.m^2)$
1433	0.796	2.511	727.6	539.871	- 72.02	0.049974
1500	0.7591	2.735	768.8	586.8473	- 74.83	0.049952
1677	0.6748	3.385	893.1	721.7256	- 82.24	0.049976
1750	0.645	3.671	949.6	780.7414	- 85.3	0.049961
1800	0.6259	3.879	991	823.2063	- 87.39	0.05
1900	0.5904	4.309	1078	910.9871	- 91.58	0.050012
2000	0.5585	4.763	1171	1002.762	- 95.77	0.049997

Table 5: Load characteristic for DC Shunt Motor (I_f = 0.6748 A)

Case	T_L (N-m)	I_a (A)	I_{in} (A)	N_r (rpm)	T_e (N-m)	P_{in} (W)	η (%)
No-load	0.6	3.382	4.0568	1677	4.083	892.5	11.8052
Full-Load	14.75	14.72	15.395	1499	17.81	3388	68.3356
Max. Efficiency	19.99	18.92	19.595	1433	22.88	4311	69.5789

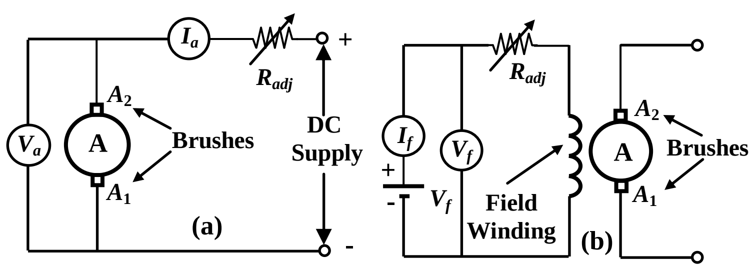

Fig. 1: a) Measurement of Armature & b) Field Resistances

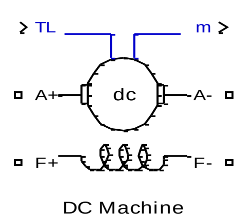

Fig. 2: DC Machine Block

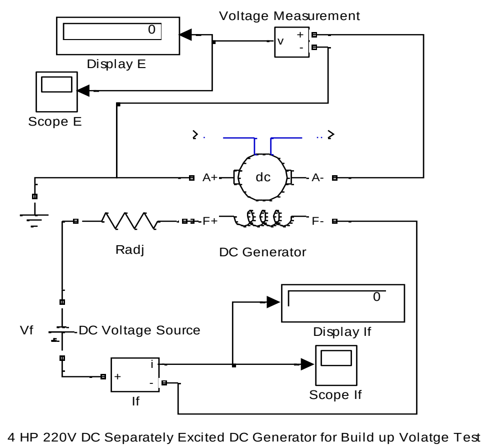

Fig. 3: OCC Test Diagram for Separately Excited DC Generator

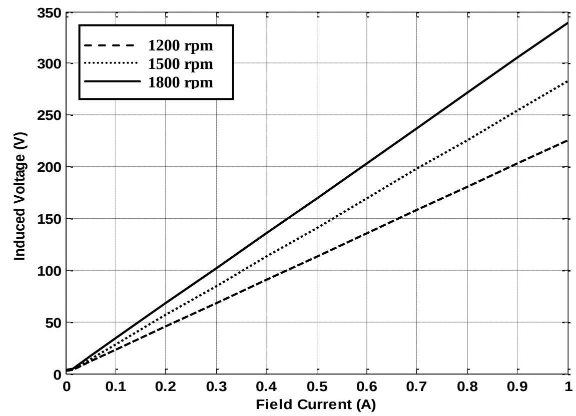

Fig. 4: No-load Characteristic Internal Induced Voltage E as function of Field Current I_f

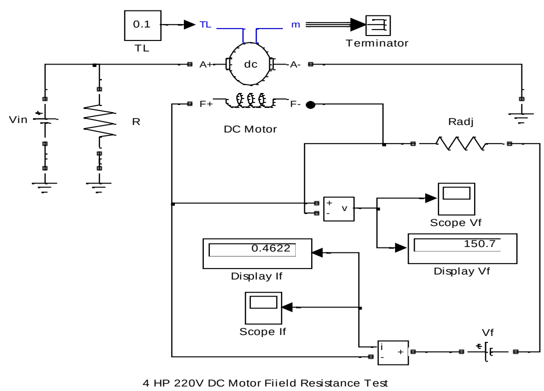

Fig. 5: Field Resistance Test Diagram

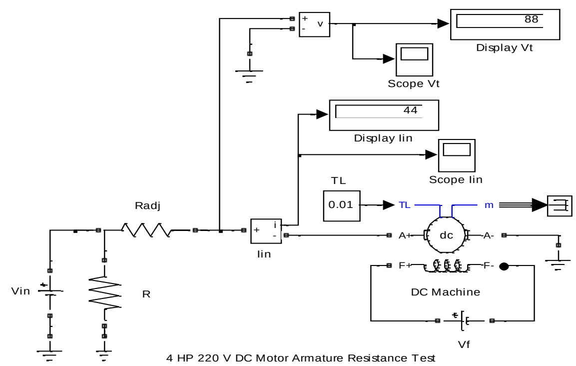

Fig. 6: Armature Resistance Test Diagram

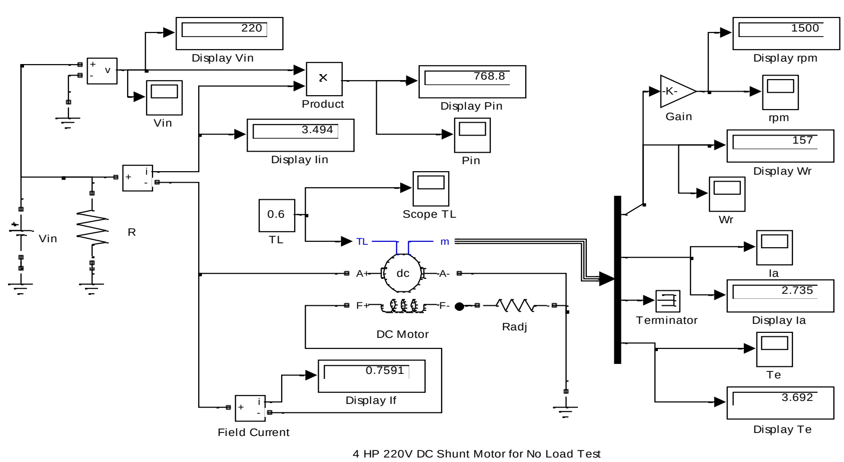

Fig. 7: No load Test for DC Shunt Motor

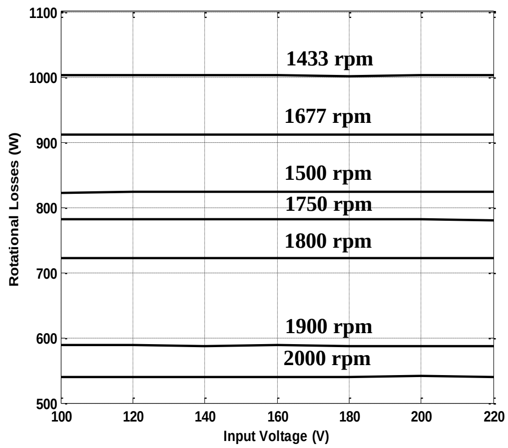

Fig. 8: Set of the Rotational Losses as a Function of Input Voltage at Various Constant Speeds

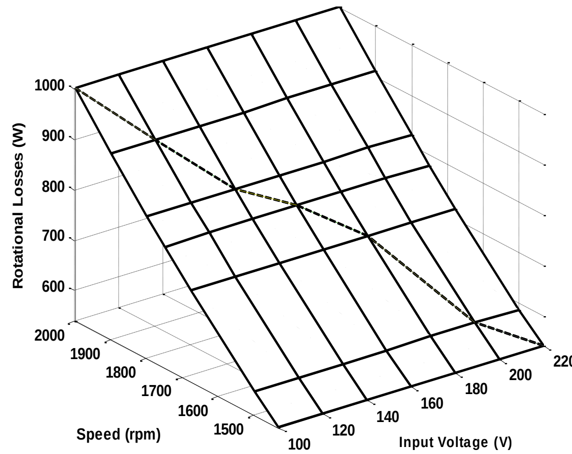

Fig. 9: the Rotational Losses as a Function of both Machine Input Voltage and Speed

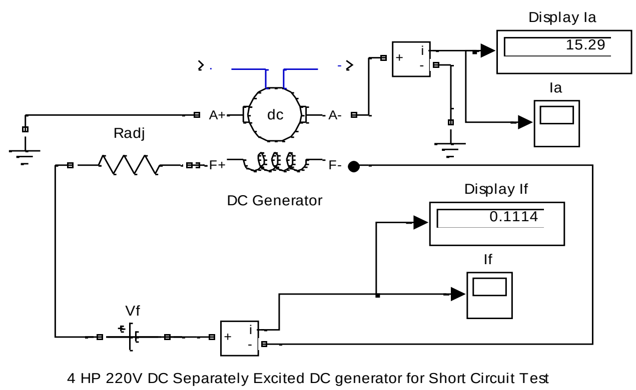

Fig. 10: Short Circuit Test for Separately Excited DC Generator

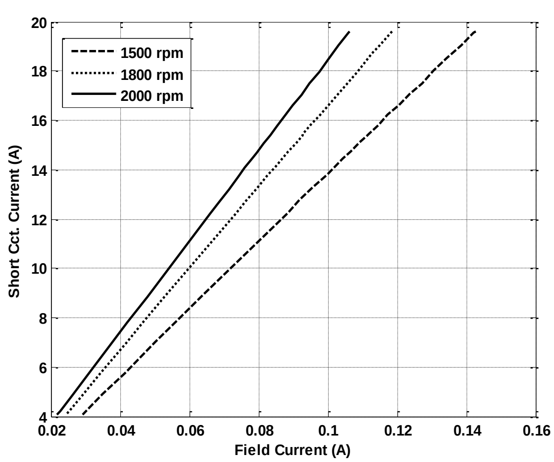

Fig. 11: the Variation of the Short Circuit Current as a Function of Field Current for Different Speeds

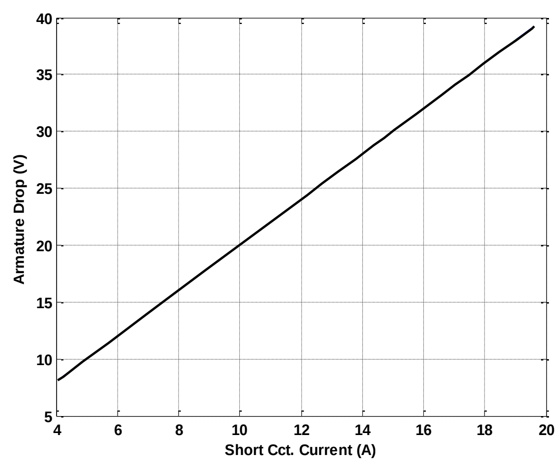

Fig. 12: the Armature Drop V_a at any Short Circuit Load Current I_{sc}

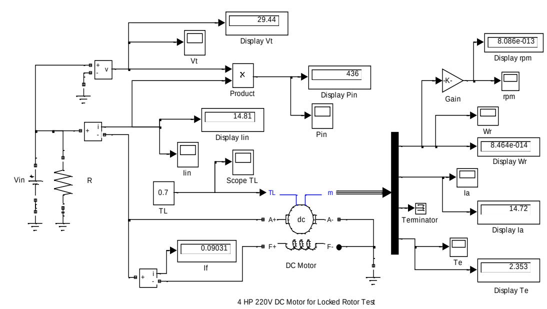

Fig. 13: Locked Rotor Test Diagram

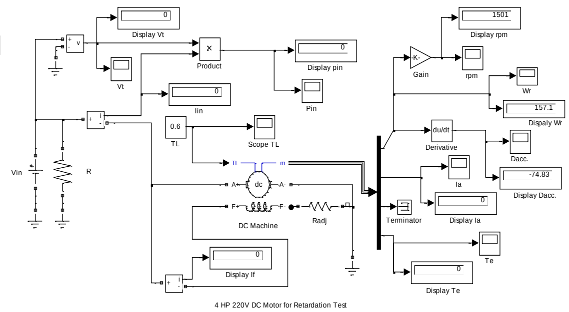

Fig. 14: Retardation Test Diagram for Measuring the Rotor Moment of Inertia

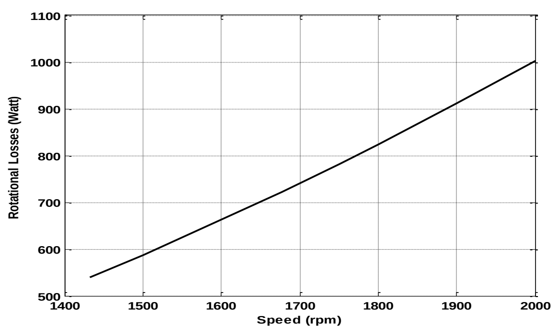

Fig. 15: the Rotational Losses as a Function of Speed for Constant Input Voltage

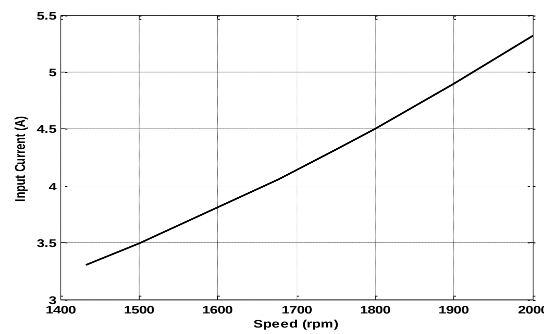

Fig. 16: the Input Current as a Function of Speed for Constant Input Voltage

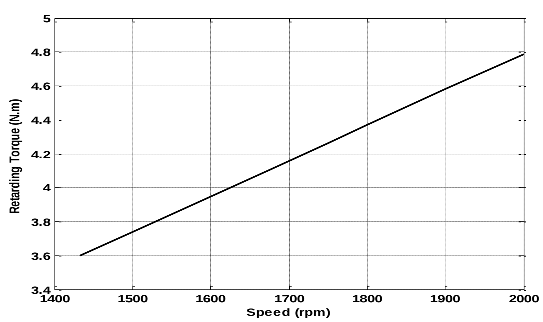

Fig. 17: the Retarding Torque T_{lost} as a Function of Initial No-load Speed

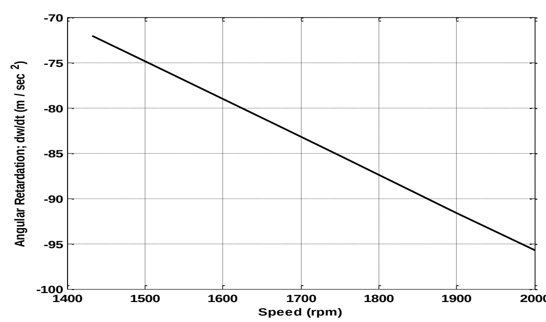

Fig. 18: the Rotor Deceleration $d\omega/dt$ as a Function of Initial No-load Speed

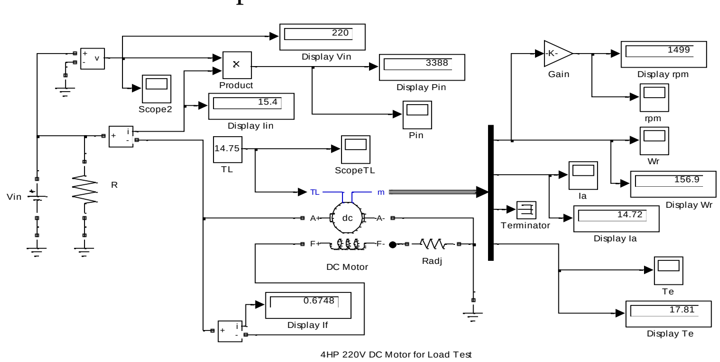

Fig. 19: Load Test Diagram for DC Shunt Motor

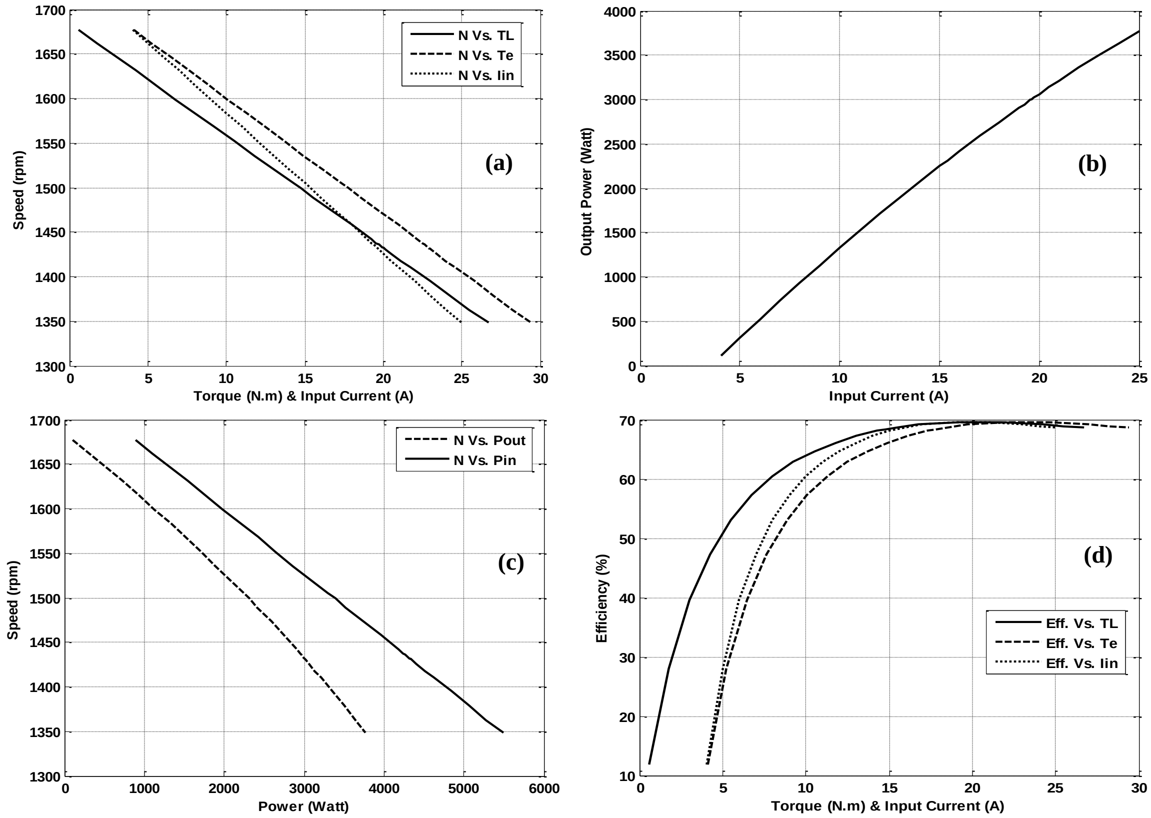

Fig. 20: Load Characteristics; a) the Motor Speed as a Function of Torque (T_L & T_e) and Input Current, b) the Output Power as a Function of Input Current, c) the Speed as a Function of Input and Output Power, and d) the Efficiency as a Function of Torque, and Input current

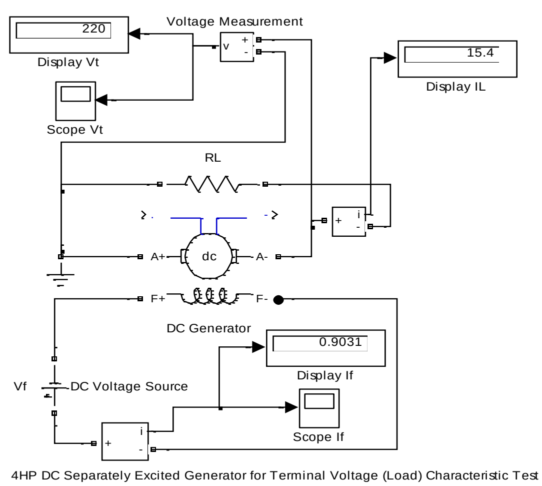

Fig. 21: Load Test Diagram for Separately Excited DC Generator

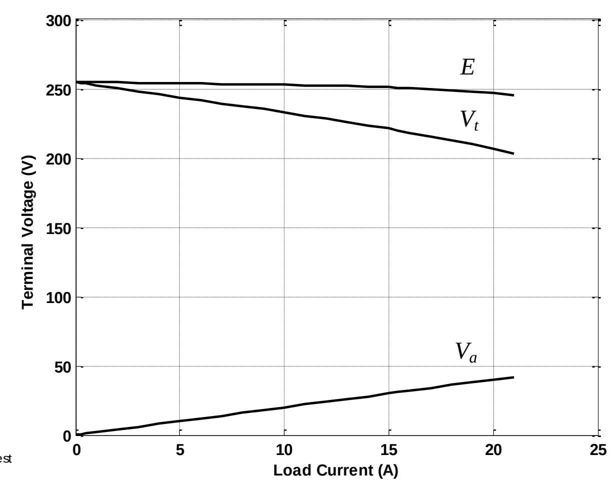

Fig. 22: Load Characteristic; Terminal Voltage as Function of Load Current