Terminal Characteristics Studies of a MATLAB Simulink-Based Model of Shunt DC Motor

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***Abstract*—This paper comprehensively investigates Shunt DC motors, using MATLAB/Simulink for modeling and simulation. The emphasis lies in understanding the magnetization curves, terminal characteristics, and speed control methods inherent to these motors. The simulation results encompass the analysis of the magnetization curve, terminal characteristics, and the consequential effects of speed control methods on motor performance. The outcomes affirm the reliability and versatility of shunt DC motors, providing valuable insights for the broader understanding of electromechanical systems.**

***Keywords*— Shunt DC motor, terminal voltage, field current, magnetic flux, non-linearity**

I. INTRODUCTION

DC motors are electromechanical devices that convert electrical energy into mechanical energy. They are primarily used in applications requiring variable speed control and high torque [1]. Shunt DC motors are one of the most common types of DC motors due to their simple construction, ease of control, and wide speed range. A shunt DC motor, often referred to as a shunt wound DC motor, belongs to the category of self-excited DC motors. The field windings can be connected in parallel with the armature winding in this motor type. Consequently, both windings receive the same terminal voltage from the power supply, ensuring a consistent speed regardless of the load. Characterized by a steady speed and low starting torque, the DC shunt motor operates reliably under various conditions.

The construction of a shunt DC motor involves several key components meticulously arranged to facilitate efficient operation. At its core, a shunt DC motor comprises an armature, field windings, commutator, and brushes. The armature, typically made of a cylindrical coil of wire, is centrally positioned and rotates within the magnetic field created by the field windings [3]. These field windings, consisting of wire wrapped around a core, generate the magnetic field when connected in parallel with the armature.

The commutator, a segmented rotary switch, reverses the current direction in the armature coil at specific points during its rotation, ensuring a continuous and unidirectional torque [2].

Brushes, typically made of carbon, maintain electrical contact with the commutator, allowing current flow. The shunt DC motor's simplicity in design, with the field windings connected in parallel (shunt) to the armature, contributes to its ease of control and wide speed range, making it a popular choice in various applications. The equivalent circuit of a shunt DC motor provides a simplified representation that aids in analyzing and understanding its electrical characteristics. The circuit diagram is shown below.

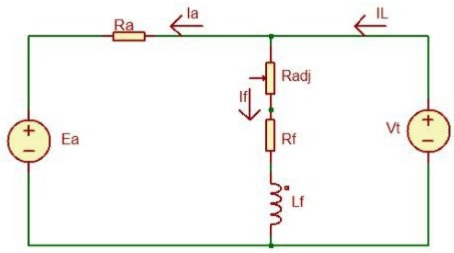

Fig. 1. The equivalent circuit of a shunt DC motor

E_a *is the internally generated voltage.*
R_a *is the armature resistance.*
R_{adj} *is the adjusted field resistance.*
R_f *is the field resistance.*
L_a *is the field inductance.*

A. Objectives

The primary objective of this paper is to investigate the torque-speed characteristics of the Shunt DC motor modeled in MATLAB/Simulink. Further, the magnetization curve and speed control techniques, such as resistance armature and field resistance control, are also investigated and plotted to better understand the theory.

II. METHODOLOGY

A. Components

The main component used for this simulation was the DC machine block in Simulink, shown in the figure below.

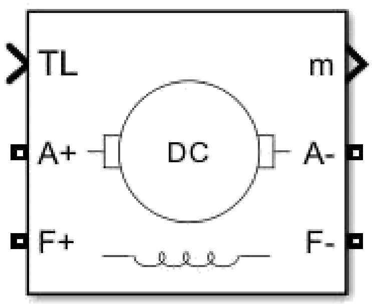

Fig 2. DC Machine block in Simulink

The present block provides access to the field and armature connections so that the machine can be used as a shunt-connected DC motor—This can be realized by simply connecting the port (A+, A-) and (F+. F-) in parallel with the same DC voltage source (Fig.3). This Simulink block also provides three inputs which are the torque load (Nm), the speed (rad/s), and the mechanical rotational port on the one hand; on the other hand, there are four outputs: the speed of the machine in rad/sec, the armature current and the field current in ampere, and the induced torque in Nm—all of these outputs can be accessed from the port m of the DC machine block. Further, this block comes with a handful number of preset models. For the simulation in this paper, the preset model 04 was chosen. As such, the shunt DC motor was rated 10Hp 1750 rpm 240V. This model has other fixed parameters, which are as follows:

- The armature Resistance and inductance [R_a (Ohm) L_a (H)]: [1.086 and 0.01216]
- Field resistance and inductance [R_f (Ohm) L_f (H)]: [180 and 71.47]
- And finally, the Field-armature mutual inductance L_{af} (H) of 0.6458

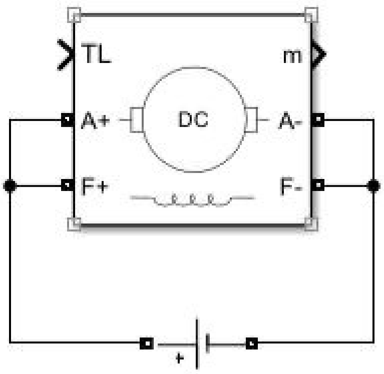

Fig 3. DC machine block connected as Shunt DC motor.

B. Magnetization Curve

One of the major objectives of this paper was to plot the magnetization curve of the shunt DC model at no-load speed (the field current I*F* against the armature voltage E_a). The no-load speed of the model presented in this paper was obtained by setting the load torque to 0 Nm and the DC voltage source at 240V. This gave a no-load speed of 2634 rpm.

To ensure that the speed stays at 2634 rpm, the input of the block was changed to "speed" and fed in with 2634 rpm, and a ramp signal (with slope 12V) was connected to the terminal voltage via a controlled voltage source. It was increased with the simulation time until it went above 240V (fig 4). This resulted in different values of the field current IF. The result, an array, was sent to the MATLAB workspace using the workspace block.

On the other hand, it is known that the internally generated voltage depends on the flux from the relation:

$$E_a = K \times \emptyset \times \omega_m \qquad (1)$$

The flux is related to the field current through a non-linear relationship. However, like many other blocks in Simulink, the DC machine block is linear and does not provide any non-linearity to plot the magnetization curve. [4] proposed a way to define the analytical dependence of the magnetization curve of the DC machine using the hyperbolic tangent.

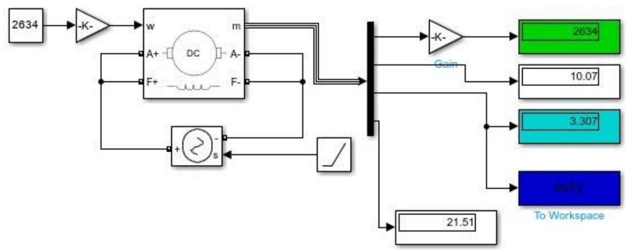

Fig 4. Field current of shunt DC motor at no-load speed (2634 rpm)

In this paper, a similar approach was used to establish the non-linearity between the internally generated voltage E_a and the field current I*F* through the expression:

$$E_a(I_F) = E_m \cdot \tanh(I_F) \qquad (2)$$

Where E_m is the maximum emf (240V) in no-load conditions. The residual emf and other factors were neglected in this analysis. The magnetization curve is shown below:

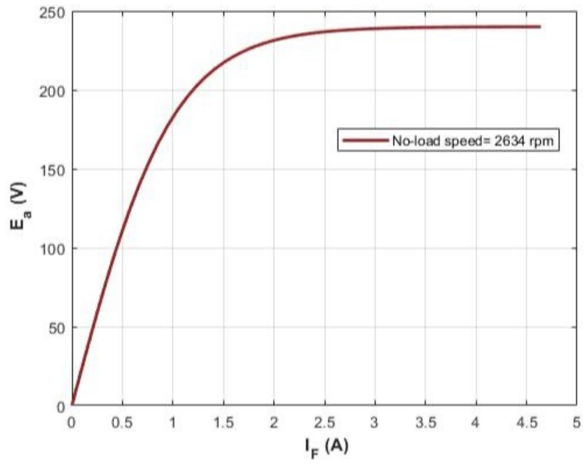

Fig 5. Magnetization curve (I*F* vs E*a*) at no-load speed (2634 rpm)

C. Terminal Characteristics of Shunt DC Motor

For a shunt DC motor, the terminal characteristic is a plot of the output quantities of the motor against each other. For this motor configuration, the plot of the shaft torque and the speed of rotation of the shaft are used.
We need to recall that to establish the relationship between the shaft torque and the shaft's rotation speed.

$$\omega_m = \frac{V_t}{K\emptyset} - \frac{R_a}{(K\emptyset)^2} \cdot \tau_{ind} \quad (3)$$

Where,

V_t = Terminal voltage for motor
τ_{ind} = Induced torque of the motor
$\emptyset$ = field flux
R_a = Armature resistance

With equation 1 in mind, the speed of the motor can be varied linearly with the induced torque by keeping the other terms in the equation, such as the terminal voltage, armature resistance, and the field flux, constant. In this scenario, a plot of the speed of the motor against the induced torque produces a linear graph, as can be seen in Fig (6).

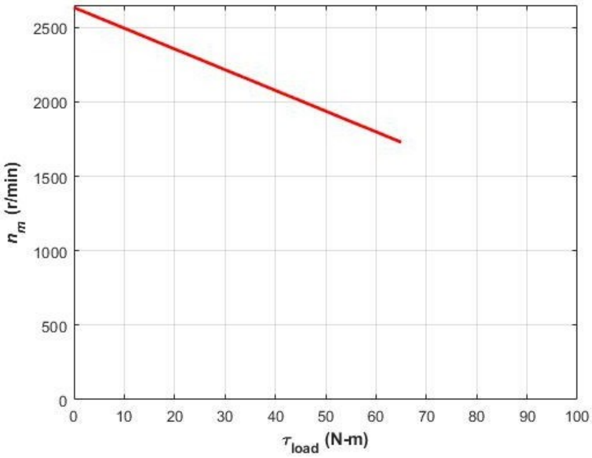

Fig 6. Torque speed characteristics graph.

D. *Speed Control of Shunt DC motor*

1. Field Resistance Speed Control Method

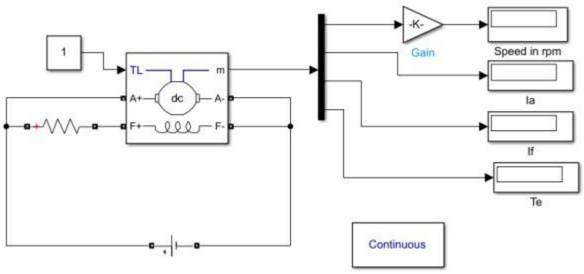

Fig 7. Field Resistance Speed Control

From (1), the speed control methods of the motor can be derived. It can be observed that the speed of the motor varies inversely to the field flux. Hence, for any increase in field flux, there will be a decrease in the speed of the motor and vice versa. The field flux of the motor can be varied by varying the resistance of the field. The relationship between the field resistance and the field flux can be established using the equation below.

$$I_f = \frac{V_f}{R_f} \qquad (4)$$

From (4), it can be observed that an increase in the field resistance leads to a decrease in the field current, which subsequently decreases the field flux from the relationship $\Phi = KI_f$. As the field flux decreases, the speed of the motor from (3) increases. Also, a decrease in the field resistance leads to a rise in the field current, subsequently increasing the field flux of the motor. As the field flux increases, the speed of the motor reduces from (3). In Fig (8) below, the torque speed characteristics of the shunt DC motor were plotted using a field resistance of 60 ohms and 40 ohms.

From Fig (8), it can be observed that when the field resistance is adjusted to 60 ohms, the motor's speed is higher than when the field resistance is adjusted to 40 ohms.

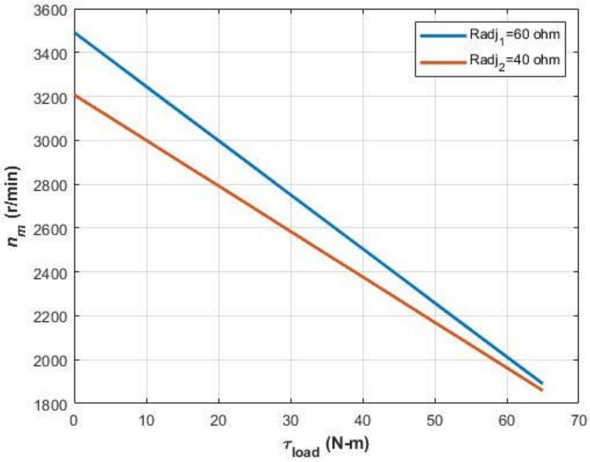

Fig 8. Torque speed characteristics of the shunt DC motor with varying field resistance.

2. Armature Resistance Speed Control Method

The Armature Resistance control is a method used to control the speed of DC motors. This method is performed by inserting a resistor in the series part of the shunt DC motor. This type of speed control is achieved by varying the armature resistance, which then changes the motor's speed. The speed control armature resistance method is the least used because it is lossy. This is because a high resistance in series with the armature windings causes two losses. As a result, this speed control method is characterized by high power losses in the armature windings and poor speed regulation. The Simulink model below shows the model used for the armature resistance speed control of the Shunt DC motor using the same preset model.

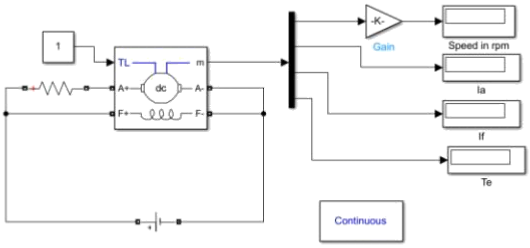

Fig 9. Armature resistance speed control

3. Result From Simulation

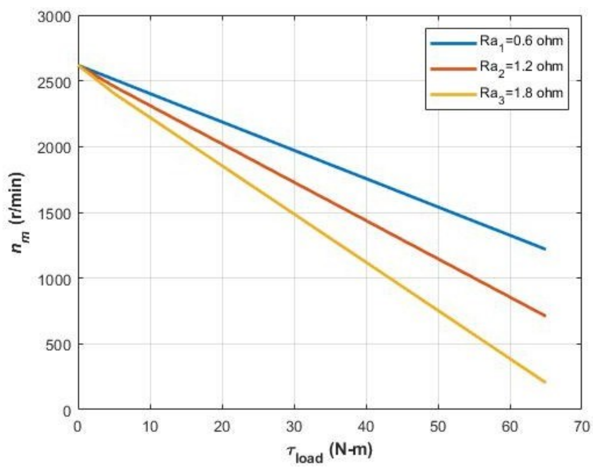

Fig 10. Armature resistance speed control

For this simulation, three different resistances were chosen. The torque-speed graph shows a negative gradient, which, in this case, is affected by armature resistance. Because there is a constant terminal voltage and the flux of the shunt DC motor is not affected by the change in armature resistance, all three variations meet at the same y-intercept value but have different slopes. Also, we can see that from the same load torque, as the armature resistance increases, the speed of the motor decreases because there is a voltage drop across the armature resistance according to Ohm's law ($V = IR$). This voltage drop reduces the effective voltage across the armature terminals, leading to a decrease in the back emf and, therefore, a reduction in the motor speed.

III. RESULTS DISCUSSION

From the simulations above, it can be observed that as the armature resistance of the shunt DC motor increases, the slope and, therefore, the speed of the motor decreases, but the intercept remains the same. It can also be observed that as the field resistance increases, the slope remains the same; however, the y-intercept changes because the field resistance directly affects the flux of the shunt DC motor. It can be stated that the model of the shunt DC motor follows the operation of an ideal shunt DC motor. On the other hand, the introduction of non-linearity through the hyperbolic tangent to relate the internally generated voltage E_a and the field current I_F was essential to plot the magnetization curve since the DC machine block on which the model of this paper is based is linear. This method was proven satisfactory and can roughly estimate the magnetization curve at no-load speed.

IV. CONCLUSION

This paper provided a hands-on and comprehensive exploration of the operational behavior of a shunt DC motor using MATLAB/Simulink. Analyzing the magnetization curve has deepened our understanding of the terminal behavior, specifically the relationship between field current and induced internal voltage at no-load speed, which is non-linear. Moreover, our exploration into speed control methods, including adjusting the field resistance and armature resistance, has highlighted vital factors influencing the motor's speed regulation.

Through this project, we have gained practical motor design and control skills and developed a profound understanding of how different parameters impact the motor's overall performance. The insights derived from this endeavor contribute significantly to our knowledge of shunt DC motors and their applications in practical engineering scenarios.

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