

## Simulation used in education for a separately excited DC motor

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**ABSTRACT:** Direct current (DC) motor education involves many complex graphs, many examples and, since class time is limited, it would appear that computer simulation is a powerful tool by which to improve the teaching. In this article simulation models to improve the teaching are presented and discussed. The simulation models for the starting, speed regulation and braking of a DC motor are presented and analysed using MATLAB/Simulink. The analysis and results show that the simulation models in the study can be used directly in and out of class, and the programming ability of the student also may be developed.

### INTRODUCTION

The DC motor has many advantages regarding starting and speed control. Therefore, it is a key component in the educational content in all specialties of mechanical engineering, such as vehicle engineering, mechatronics engineering, mechanical design, manufacture and automation. The control technology for the DC motor is very mature and many textbooks and other published literature have discussed its fundamentals, control methods and applications.

There are some DC motor software simulation models that can be used directly to design and analyse DC motor applications. The models make excellent material for education. Computer simulation is a powerful tool for education about the characteristics of DC motors. Software packages that can be used for DC motor research and education include MATLAB [1-5], RecurDyn and Colink [6].

Direct current motors can be divided into separately excited DC motors, shunt-wound DC motors, series-wound DC motors and compound-wound DC motors. The separately excited DC motor is typical and always taught at universities. Described in this article is the simulation of a separately excited DC motor, including starting, speed control and braking, as well as an analysis of the results.

### A MODEL OF THE SEPARATELY EXCITED DC MOTOR

The equivalent circuit of the separately excited DC motor is shown in Figure 1 [7][8].  $I_a$  and  $I_f$  are the armature and field currents,  $R_a$  and  $L_a$  are the armature resistance and inductance,  $R_f$  and  $L_f$  are the field resistance and inductance,  $U$  and  $U_f$  are armature and field voltages,  $n$  and  $\omega$  are the speed in r/min and rad/s, respectively,  $E$  is the back EMF (electromotive force) and  $T_e$  is the electromagnetic torque.

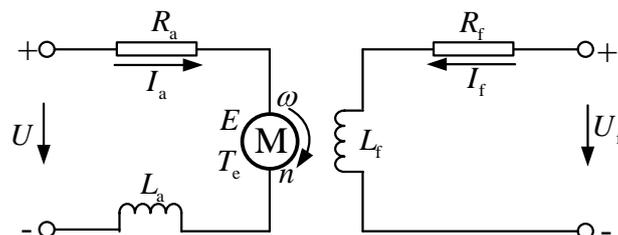


Figure 1: Equivalent circuit of the separately excited DC motor.

The key set of equations for the separately excited DC motor is listed below:

$$\begin{cases} E = K_e \phi n = K_a \phi \omega = L_{af} I_f \omega \\ T_e = K_a \phi I_a \\ U = E + R_a I_a \end{cases} \quad (1)$$

where  $\phi$  is the air-gap flux,  $K_e$  and  $K_a$  are determined by the DC motor structure and  $L_{af}$  is the field-armature mutual inductance. The speed equation is:

$$n = \frac{U}{K_e \phi} - \frac{R_a}{K_e K_a \phi^2} T_e \quad (2)$$

The simulation model was based on the equivalent circuit in Figure 1 and the Equation (1). The simulation model of the separately excited DC motor with some annotations in MATLAB is shown in Figure 2. It clearly demonstrates the essential relationship between the different parts of the motor. It is excellent material for use in education.

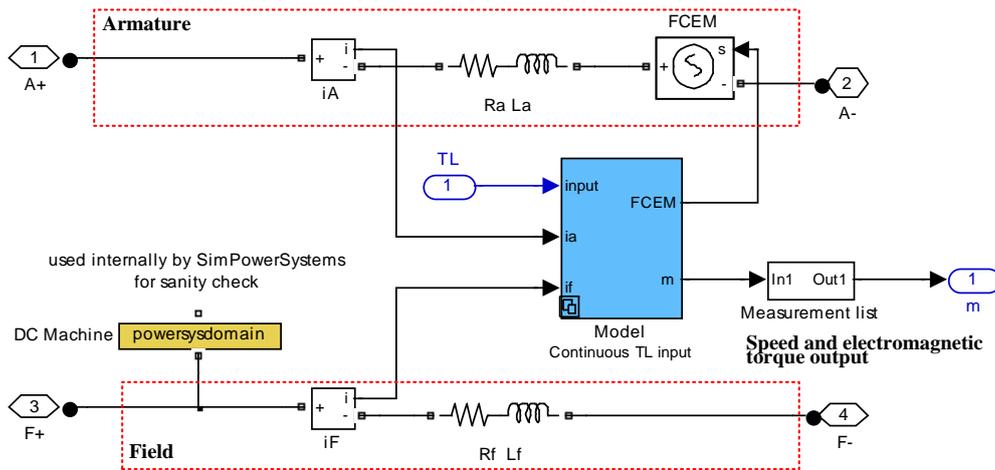
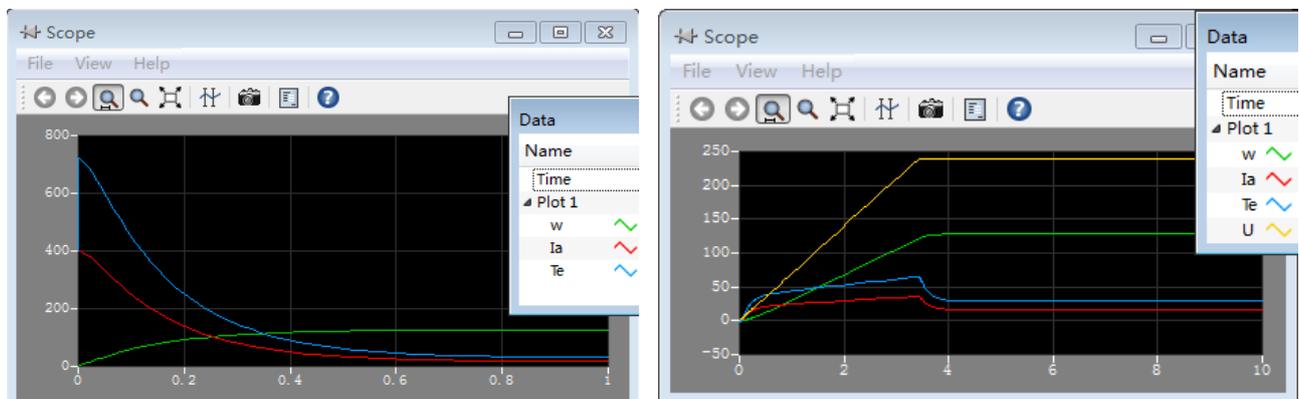


Figure 2: Simulation model of a separately excited DC motor in MATLAB/Simulink/SimPowerSystem.

### SIMULATION OF STARTING THE MOTOR

At the beginning of starting the motor, the speed  $\omega = 0$  and the back-EMF  $E = 0$ . If the full voltage is applied to the armature terminals, the armature current  $I_a$  will be excessively heavy, as shown in Figure 4a. The armature current is very heavy until the rotor runs up to full speed. The motor parameters are as follows:  $R_a = 0.6\Omega$ ,  $L_a = 0.012\text{H}$ ,  $R_f = 240\Omega$ ,  $L_f = 120\text{H}$ ,  $L_{af} = 1.8\text{H}$ , the total inertia  $J = 1\text{Kg m}^2$ , and the load torque is proportional to speed.

The simulation model corresponding to the result in Figure 3a is shown in Figure 4a. The simulation of the DC model was implemented directly using MATLAB/Simulink/SimPowerSystem. In this model, the full voltage is applied to the armature terminals. The armature current drops from about 400A to 16.25A and the electromagnetic torque from about 720N m to 29.25N m progressively as the speed increases from zero to 128rad/s.



a)

b)

Figure 3: Starting performance for a DC motor: a) starting on full voltage; and b) starting on reduced voltage.

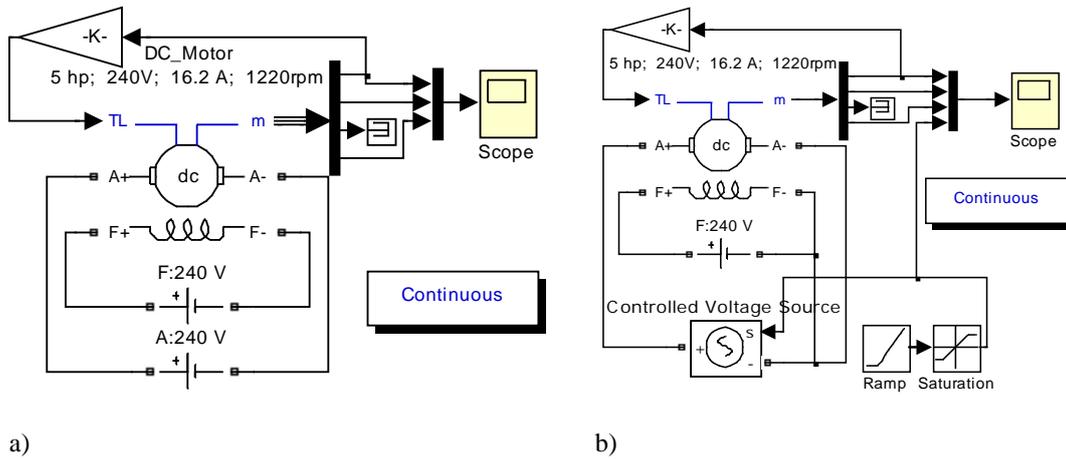


Figure 4: Simulation model for: a) starting on full voltage; and b) starting on reduced voltage.

The excessive armature current can result in excessive electromagnetic torque, which may cause many problems. For example, it can make the fuses blow or the circuit-breaker trip. The powerful torque makes the rotor accelerate rapidly, which may damage the mechanical drive system. So it is necessary to limit the starting current. The two basic types of motor starting methods are reduced voltage and connecting an external resistor in the armature circuit.

The starting voltage increases linearly with the slope of 70V/s in the simulation model as shown in Figure 4b. The simulation results are shown in Figure 3b. At about 3.43sec, full voltage is reached, and the current and torque reach the highest values, which are only 36.13A and 65.04N m.

The model power\_dcmotor.mdl with a three-step resistance starter from MATLAB/Simulink Demos was adopted and the motor parameters set as before. The three resistors have resistance values of 3.66Ω, 1.64Ω and 0.74 Ω, respectively. The switching moments are 2.8sec, 4.8sec and 6.8sec, respectively. The armature is connected to a source of 240V at 0.5sec. The simulation results are shown in Figure 5, which demonstrates that the armature current is limited.

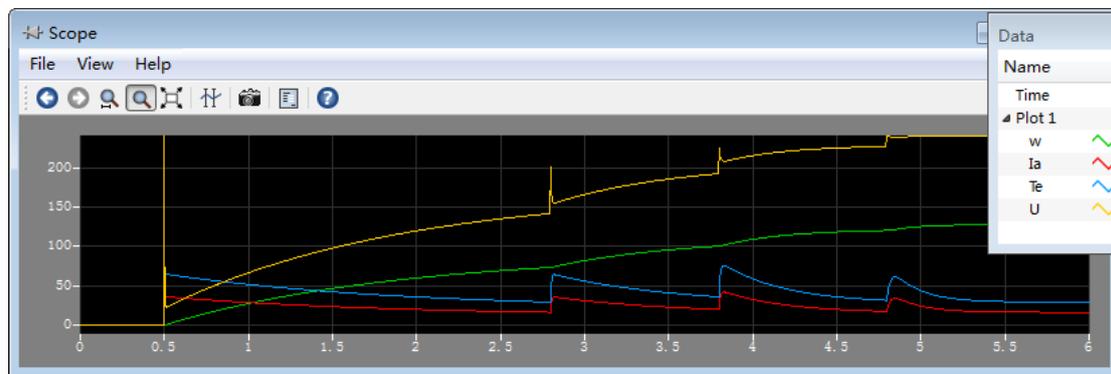


Figure 5: Starting performance for a DC motor with a three-step resistance starter.

## SIMULATION OF THE SPEED REGULATION

Three factors on the right side of Equation (2) can be adjusted to control the speed, producing three basic speed regulation methods. A first involves adjustment of the applied terminal voltage, called armature voltage control. A second is field flux control. A third method involves the use of an external resistor connected in the armature circuit, called armature resistance control.

The simulation model for the first method is shown in Figure 6a. The Lookup Table block is used to generate the desired armature voltage. This computes an approximation to some function  $y = f(x)$  given data vectors  $x$  and  $y$ . The vector of input values was [0, 3, 4, 4.001, 5, 5.001, 6, 8, 10], and the Table data block is [0, 240, 240, 160, 160, 200, 200, 100, 100]. Interpolation-Extrapolation was adopted. A step load torque with the step time of 2sec, the initial value of zero and final value of 29.2N m was imposed. The starting period was from zero to 4sec based on the reduced value of the starting voltage. The results are shown in Figure 7. The results demonstrate the obvious speed increase or decrease in response to the armature voltage.

The Embedded MATLAB Function block was used to generate the adjustment law in the simulation model shown in Figure 6b for the field flux control method. Figure 8 shows the generated armature voltage  $U$  value, field voltage  $U_F$  value and load torque  $T_L$ . The air-flux is diminished if the field voltage is decreased. In order to demonstrate the relation

between the current, torque, voltage and speed, some quantities have been multiplied by certain constants, as can be found from the Data window on the right of Figure 8.

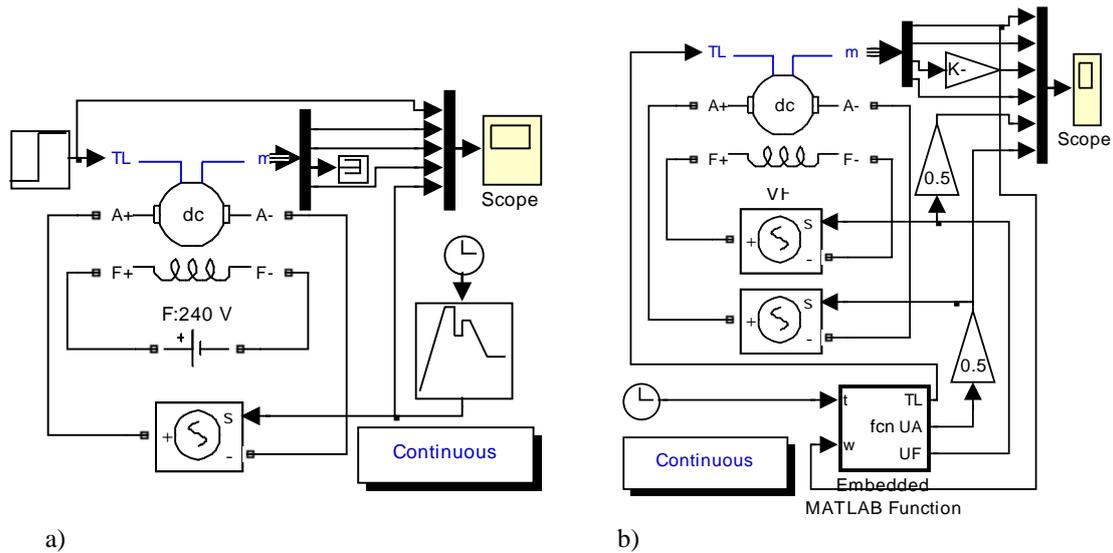


Figure 6: Simulation model for speed regulation using a) armature voltage control; and b) flux-weakening control.

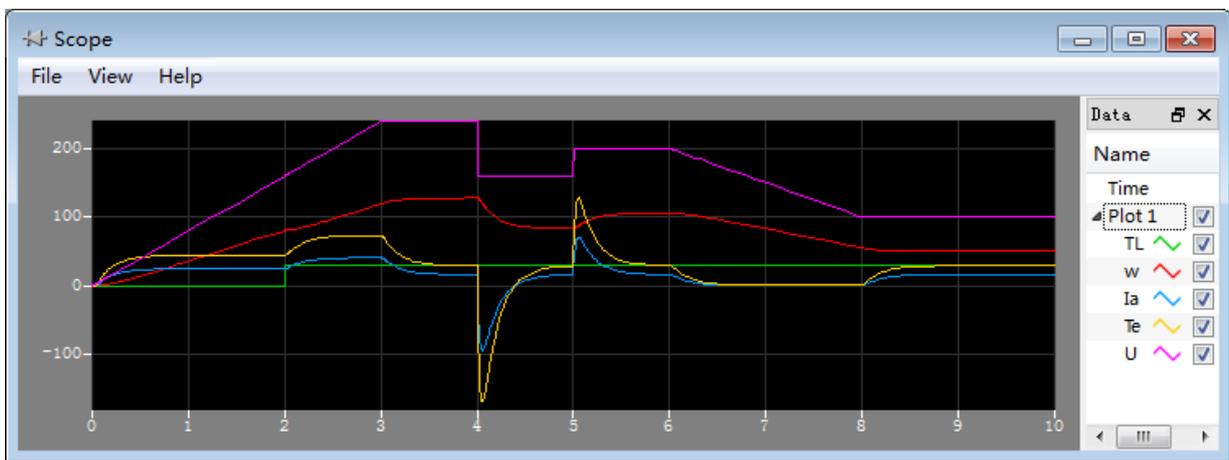


Figure 7: Performance of a DC motor with armature voltage control.

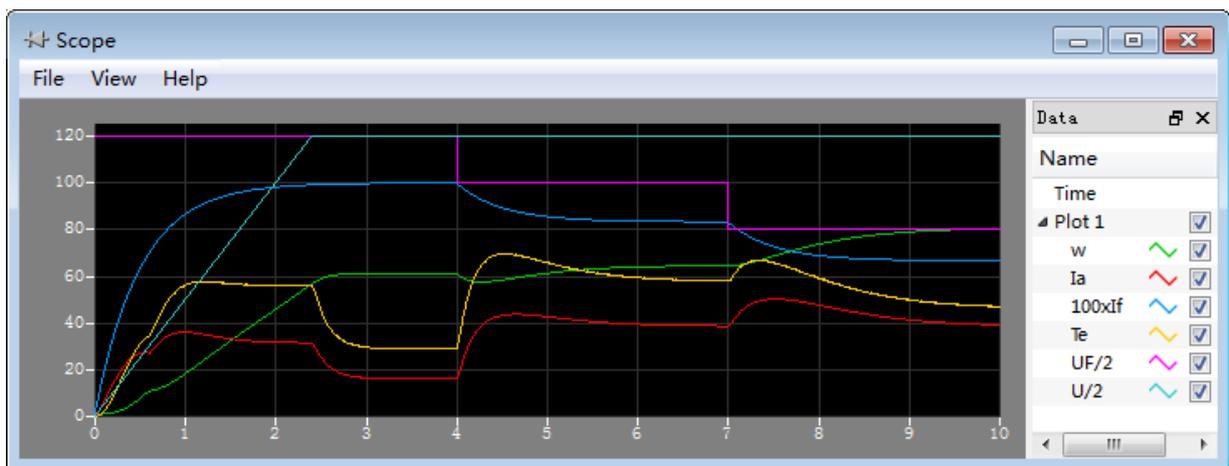


Figure 8: Performance of a 5HP, 240V DC motor with field flux control.

The model `power_dcmotor.mdl` in MATLAB/Simulink Demos was modified for the third speed regulation method. Five external resistors connected in the armature circuit are shown in Figure 9a. The five resistance values are:  $R_1 = 3.66\Omega$ ,  $R_2 = 1.64\Omega$ ,  $R_3 = 0.74\Omega$ ,  $R_4 = 1.64\Omega$ ,  $R_5 = 0.74\Omega$ . The switching moments are 15sec, 25sec, 35sec, 45sec and 55sec, respectively. The total resistance value in the armature circuit is divided into six steps:  $R_1 + R_2 + R_3 + R_4 + R_5 + R_a$ ;  $R_2 + R_3 + R_4 + R_5 + R_a$ ;  $R_3 + R_4 + R_5 + R_a$ ;  $R_4 + R_5 + R_a$ ;  $R_5 + R_a$ ;  $R_a$ .

The corresponding speed-torque curves are shown in Figure 9b with the dashed line. The simulation speed-torque performance is shown in Figure 9b with the solid red line. It should be noted that the six speed-torque curves with the dashed line were added into the figure after simulation.

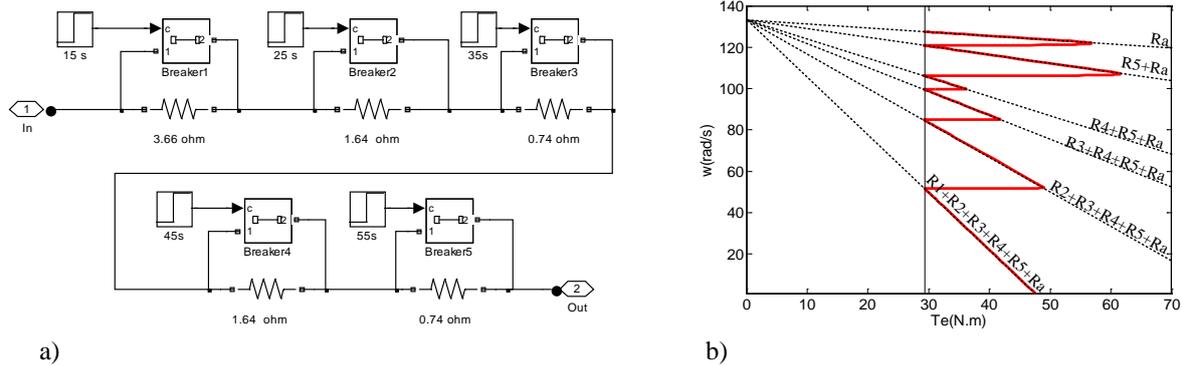


Figure 9: Simulation model and results for a DC motor with a 6-step resistance; a) simulation model; and b) simulation results for speed-torque.

### SIMULATION OF BRAKING

There are three braking methods: regenerative braking, plugging or reverse current braking, and dynamic braking or rheostatic braking. If the speed exceeds the no-load value, regenerative braking works. In rheostatic braking, an external resistance is connected in the armature in place of the DC supply. Plugging or reverse current braking is by reversing the power lines.

This example is for the regenerative braking. A load torque of 29.2N.m was imposed for an initial 4 seconds. After this, the load torque was -10N m. From the simulation results shown in Figure 10, the motor speed increases and the armature current decreases. As the speed increases, the net voltage ( $U - E$ ) decreases and so does the armature current. The motor continues to accelerate until the electromagnetic torque reaches -10N m. The speed reaches the no-load value at 4.245sec. At 4.25sec, the armature voltage is equal to the back EMF, so the armature value becomes zero. After 4.25sec, the armature voltage is higher than the back EMF, so the armature current flows in the reverse direction and the electromagnetic torque is in the reverse direction, indicating a braking operation.

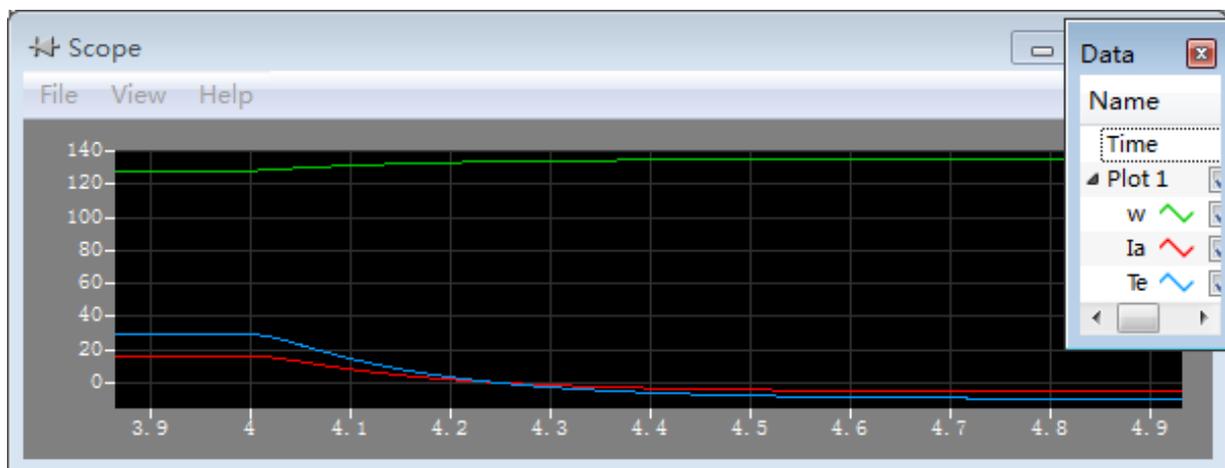


Figure 10: Simulation results for a DC motor with regenerative braking.

### IMPACT ON ENGINEERING EDUCATION

The simulation methods and models presented above have been used in classroom teaching and extracurricular training for undergraduate and graduate students in the mechanical engineering discipline. Through discussion with other teachers, surveys from the students and long-term observations, this educational method has had these significant effects:

- Studying becomes more interesting and inspiring. There are many complex diagrams and characteristic curves, such as the speed regulation with a several-step resistance shown in Figure 9b. The static ones in textbooks make analysis and study tedious and discourages the students. Computer simulations can dynamically exhibit the status of the motor when running, which makes the motor's characteristics and operation easily understood.

- The motor characteristic and running status can be demonstrated and compared more conveniently. The Scope block displays the simulation results. The Scope block can have multiple axes and all axes have a common time range with independent y-axes. The user can adjust the amount of time and the range of input values displayed. Several motor characteristic curves, such as the current, voltage and torque shown in Figure 7 and Figure 8 can be displayed together in a graph, so the student observes the results in specified time slots, thereby, facilitating comparisons.
- The status of the motor running in extreme conditions can be demonstrated and analysed. Hence, education using simulations can be greatly expanded. In physical experiments with real motors, incorrect operation or faulty equipment may result in excessively high voltage or heavy current that could greatly endanger the student and the equipment. Using computer simulations, the students can adjust the experimental parameters, start or stop the motor at will and do not need to worry about their safety or damaging equipment. So, some educational activities that are potentially dangerous in a physical experiment can be carried out easily using simulations. But the teacher should emphasise the danger in extreme conditions in practical applications.

## CONCLUSIONS

Direct current motor education involves many complex graphs and many examples. Since class time is limited, it would appear that computer simulation is a powerful tool for improving teaching. In the work outlined in this article, simulation models in MATLAB/Simulink were presented for the starting, speed regulation and braking of a DC motor. These simulation results are useful for education. The simulation methods reported in this study have several advantages. For example, the teacher and students can use the models directly in class and out of class, and this approach can cultivate the programming ability of students. Future work will develop simulation models for other kinds of DC motors.

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