

Realization of Power Electronic Converter Based DC Motor Speed Control Methods Using MATLAB/Simulink*

AYETÜL GELEN, SAFFET AYASUN

Department of Electrical and Electronics Engineering, Nigde University, Nigde 51100, Turkey. E-mail: agelen@nigde.edu.tr sayasun@nigde.edu.tr and saffetayasun@yahoo.com

The MATLAB/Simulink realization of DC motor speed control methods is achieved here by controlling the voltage applied to the armature circuit using various controlled and uncontrolled power electronic converters. The power electronic converters used in simulation models include full-bridge diode rectifier, half controlled rectifier and pulse width modulated (PWM) chopper. These simulation models are developed as a part of a software laboratory to support and enhance undergraduate electric machinery courses at Nigde University, Turkey.

Keywords: DC motors, speed control; armature voltage control; education; MATLAB/Simulink

INTRODUCTION

THE RECENT STEADY DECLINE in enrollment and interest in electric machinery courses has led to concerted efforts to address various factors and to find possible solutions. Educators agree that many engineering students consider the electric machinery courses old-fashioned and unexciting, and this lack of interest, in turn, seriously limits their ability to understand and appreciate the wide-ranging applications of electric machines [1]. Therefore, electric machinery courses are facing particularly strong pressure for change, and need to be restructured and modernized to attract more students. One convenient and yet the powerful way is to integrate up-to-date computer hardware and software tools in both lecture and laboratory sections of the machinery courses [1, 2]. Such a machinery course also meets the expectations of today's students who want to use computers and simulation tools in every aspects of a course. For this reason, computer modelling and simulation tools have been extensively used to support and enhance electric machinery courses [2–8].

MATLAB with its toolboxes such as Simulink [9] and SimPowerSystems [10] is one of the most popular software packages used in electrical engineering education to enhance teaching of electric machines [1–3], [6–8], [11–13], real-time control of DC motors [14, 15] and power electronic circuits [16].

Simulation models of transformer and induction motor's tests have already been developed using MATLAB/Simulink and successfully integrated into electric machinery courses at Nigde University

[6, 7]. A software laboratory has been designed to incorporate the simulation models into the laboratory section of the course. The software laboratory enables students to simulate the no-load and short circuit tests of transformers, and DC, no-load and blocked-rotor tests of induction motors. It has been reported that the simulating transformer or induction motor tests before the hardware experiments help students to clearly understand the experimental procedure, and simulation models complement laboratory practices [6, 7]. In order to have a complete set of simulation tools for electric machinery experiments, simulation models of speed control experiments of DC motors, namely field resistance control, armature voltage control and armature resistance control methods have been developed and included in the previously designed software laboratory [8]. It has been shown that simulation models correctly predict the effect of field resistance, armature voltage and resistance on the torque-speed characteristic of the DC motor.

However, in developing the simulation models of speed control experiments, ideal DC voltage sources have been used to drive both the field and armature circuits of the DC motor [8]. When a DC motor is driven from an ideal DC voltage source, the torque-speed characteristic becomes linear [8, 17]. In practice, DC motors are driven from a power electronic converter such as a controlled or uncontrolled rectifier rather than a DC voltage source, thus, nonlinear torque-speed characteristics might be observed in the motor performance. To reflect true characteristics of the motor operation, the simulation model of the armature voltage speed control method that uses power electronic converters to drive the DC motor needs to be developed. To the best of our know-

* Accepted 25 June 2008.

ledge, there is only one study in the literature that develops a PC-based CAD program called PC-DCM to investigate the impact of various drives such as DC voltage source, chopper and semi-converter phase controlled drives on the linearity of the torque-speed characteristics of DC motors [18].

Our purpose was to develop simulation models of the armature voltage speed control method with various drive types using MATLAB/Simulink and to illustrate how the linearity of torque-speed characteristics is affected by different drives. The realization of Simulink models was the first main contribution. The following drive types were used to supply the armature voltage:

- i) Full-wave bridge diode rectifier with and without a filter,
- ii) Half-controlled rectifier with and without a filter,
- iii) Pulse width modulated (PWM) chopper drive.

When compared to the above study [18], our work included an additional drive, full-wave bridge rectifier. In addition, the effect of LC filters commonly used in rectifiers on the linearity of the torque-speed characteristics also not reported in [18] was investigated.

The proposed simulation models complete our previous work that reported the Simulink models of induction motors and transformers' tests, and speed control experiments of DC motors (armature voltage control using a ideal DC voltage source, field resistance control and armature resistance control) in a series of published papers [6–8]. Moreover, all simulation models have been combined, and an Electric Machinery Experiment Toolbox (EMET) has been designed using MATLAB's graphical user interface programming to offer students a complete set of simulation models of electric machinery experiments in a single and easy-to-use software package.

The simulation models of DC motors have been integrated into a senior level electric machinery course to enhance the teaching of the steady-state and dynamic analysis of DC motors. The enhancement has been achieved by using the simulation models for various educational activities such as classroom demonstration, exercises and assign-

ments. It has been observed that with the help of simulation results, students increase their understanding of DC motor characteristics and dynamic behaviour, and power electronic converters and their effects on the torque-speed characteristics beyond the understanding they gain from classroom lectures and textbooks. Even though the course is designed for power systems and electric machinery majors only, it is observed that students from other major areas such as control, power electronics and systems have shown tremendous interest in the course. As a result of this, we have observed a 30 per cent (in average) increase in the enrollment of the course for the last two years.

TORQUE-SPEED CHARACTERISTIC AND SPEED CONTROL METHODS

The equivalent circuit shown in Figure 1 is used to analyse the torque-speed characteristic of DC motors. In this figure, V_T is the terminal voltage applied to the motor, I_F , R_F , and L_F are the current, resistance, and inductance of the field circuit, respectively; I_A , R_A and L_A are the current, resistance, and inductance of the armature circuit, respectively; E_A is the generated speed voltage; ω_m is the angular speed of the motor; T_e and T_l are the electromagnetic torque developed by the motor and the mechanical load torque in the opposing direction. The generated speed voltage, electromagnetic torque and volt-ampere equations of the armature circuit are given as follows [17]:

$$E_A = K\phi\omega_m \quad (1)$$

$$T_e = K\phi I_A \quad (2)$$

$$V_T = E_A + R_A I_A \quad (3)$$

where K is the design constant depending on the construction of the motor and ϕ is magnetic flux in poles.

From these equations, we can gain an understanding of the torque-speed characteristics of a DC motor. Using (1)–(3) and equivalent circuit of Figure 1 under steady-state conditions, the torque-speed characteristic of a shunt or separately excited DC motor is described by [17].

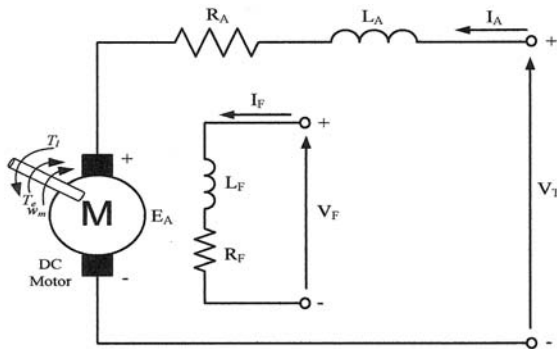


Fig. 1. Equivalent circuit of separately excited DC motor.

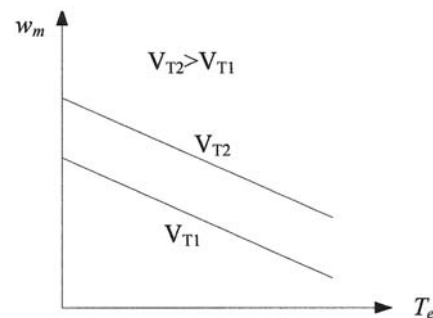


Fig. 2. Illustration of effect of armature voltage change on torque-speed characteristic.

$$\omega_m = \frac{V_T}{K\phi} - \frac{R_a}{(K\phi)^2} T_e \quad (4)$$

As (4) indicates, the torque-speed characteristic is represented by a straight line with a negative slope when the DC motor is driven from an ideal DC source. This characteristic is illustrated in Figure 2. For the speed of the motor to vary linearly with torque, the terminal voltage V_T and the flux ϕ must remain constant as the load changes. From (4), it is clear that the speed of a DC motor can be varied by controlling the field flux, the armature resistance or the terminal voltage applied to the armature [17]. Since we are interested in a Simulink model of speed control method by controlling the terminal voltage applied to the armature using various controlled and uncontrolled power electronic converters, only the armature voltage control method is briefly described.

In the armature voltage control method, the voltage applied to the armature circuit, V_T is varied without changing the voltage applied to the field-circuit of the motor. Therefore, the motor must be separately excited to use armature voltage control as shown in Figure 1. Typically a power electronic converter or a motor-generator set is required to provide the controlled armature voltage for the motor. The effect of increasing the armature voltage on the torque-speed characteristic is illustrated in Figure 2. Observe that the no-load speed of the motor increases while the slope of the curve remains unchanged since the flux is kept constant in this method. By the armature voltage control method, it is possible to control the speed of the motor for speeds below base speed but not for speeds above base speed. In order to achieve more than the base speed, an excessive armature voltage is required, which can damage the armature circuit [17].

MATLAB/SIMULINK MODELS OF SPEED CONTROL METHODS

The following power electronic converters are used to drive the armature circuit in the armature voltage control speed method:

- i) Full-wave bridge diode rectifier with and without a filter,
- ii) Half-controlled rectifier with and without a filter,
- iii) PWM chopper.

For each converter used, the torque-speed characteristics are determined. A 5-HP DC motor of 240-V rating 1220 rpm is used in the simulation models. The equivalent circuit parameters of the DC motor used in the simulation are $R_F = 240\Omega$, $L_F = 120H$, $R_A = 0.6\Omega$, $L_A = 12mH$.

Speed control method using full-wave bridge diode rectifier

Figure 3 shows the Simulink realization of the armature voltage speed control method using full-wave bridge diode rectifier. The armature circuit is supplied from full-wave bridge rectifier (universal bridge in the Simulink model) without a filter. The field circuit is separately excited from an ideal DC voltage source as $V_F = 240 V$. A DC motor block of SimPowerSystems toolbox is used. An access is provided to the field connections (F+, F-) so that the motor model can be used as a shunt-connected. The field circuit is represented by an RL circuit, (R_F and L_F in series) and 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_A 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 dialogue box. The output port (*port m*) allows

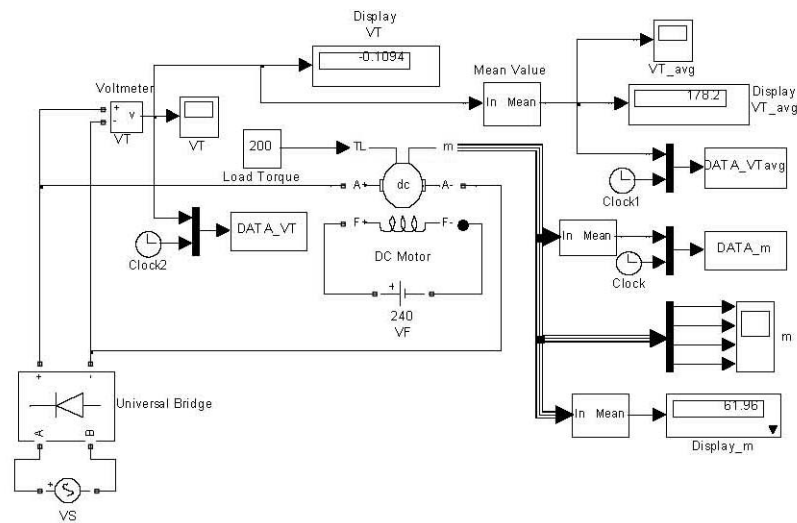


Fig. 3. MATLAB/Simulink realization of armature voltage speed control method using full-wave bridge diode rectifier.

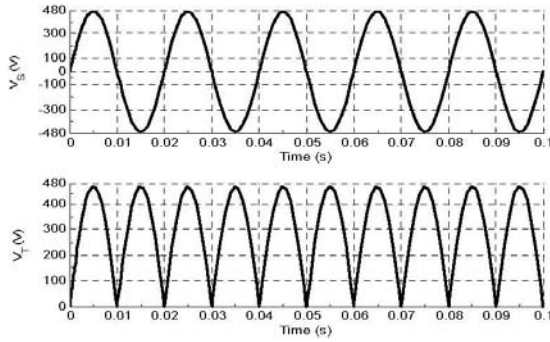


Fig. 4. Full-wave bridge rectifier input and output waveforms with 300 V mean value.

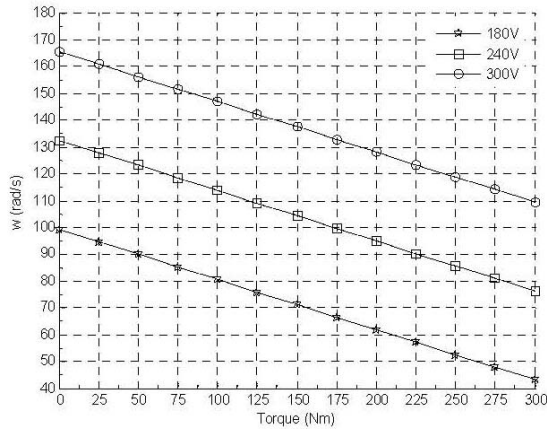


Fig. 5. Torque speed characteristics for three different armature voltages.

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 (rad/s), or the corresponding data can be written to MATLAB's workspace using the data box to employ other graphical tools available in MATLAB.

To investigate the effect of armature voltage on the torque-speed characteristic, three different armature voltages with average values $V_T = 180$, 240 and 300 V were applied while the voltage applied to the field circuit is kept constant at its nominal value $V_F = 240$ V. Full-wave bridge rectifier input and output waveforms for mean value of 300 V are given in Figure 4.

Figure 5 compares the torque-speed characteristics for the motor driven from a full-wave bridge rectifier without a filter. The simulations are run for several values of load torque in the range of $T_L = 0 - 300$ Nm to determine the steady-state value of the speed at each load level. Figure 5 clearly illustrates that the torque-speed characteristics are virtually linear and equally spaced similar to the case where the DC motor is driven from a constant DC voltage source [8, 17]. Moreover, it is

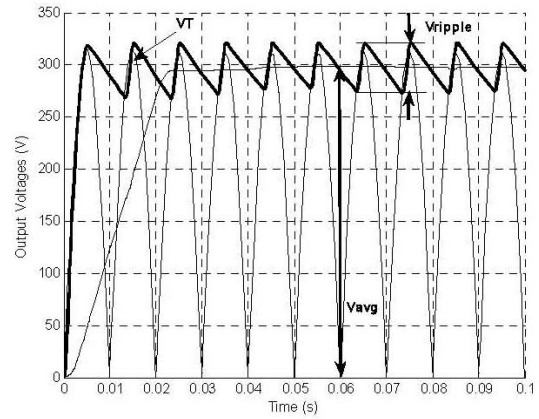


Fig. 6. Output voltages of bridge rectifier with LC filter.

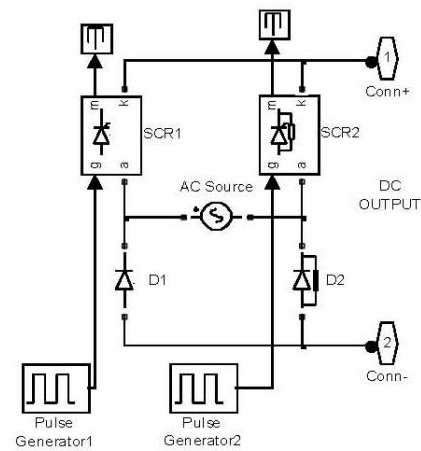


Fig. 7. MATLAB/Simulink model of half-controlled full-wave bridge rectifier.

shifted upward by increasing the armature voltage while the slope of the curve remains unchanged.

To realize a more practical speed control method, an LC filter is implemented at the output of the rectifier shown as a universal bridge in Figure 3. Choosing appropriate values of LC filter, the rectifier output could be easily smoothed with a desired ripple factor. Figure 6 shows waveform of rectifier output with a mean value of approximately 300 V for the load torque $T_L = 200$ Nm. As can be seen from Figure 6, the voltage applied to the armature circuit is much smoother when compared with the one shown in Figure 4. Torque-speed characteristics for different armature voltages with average values $V_T = 180$, 240 and 300 V are obtained to investigate the filter effects on the torque-speed characteristics. It is observed that the torque-speed characteristic is approximately the same as that for the case without a filter shown in Figure 5. For this reason, these characteristics are not given here. Such a result is expected since mean values of the voltage applied to the armature are virtually the same for both cases even though the waveforms are significantly different (see Figures 4 and 6).

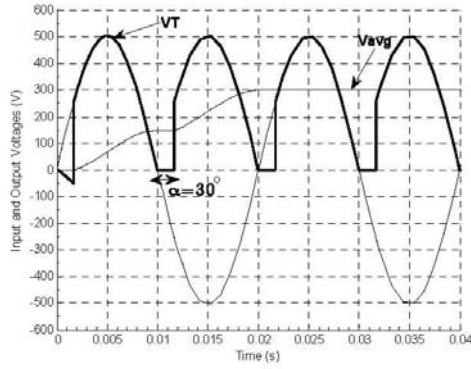


Fig. 8. Input, output waveforms and output voltage average of half-controlled full-wave bridge rectifier without filter.

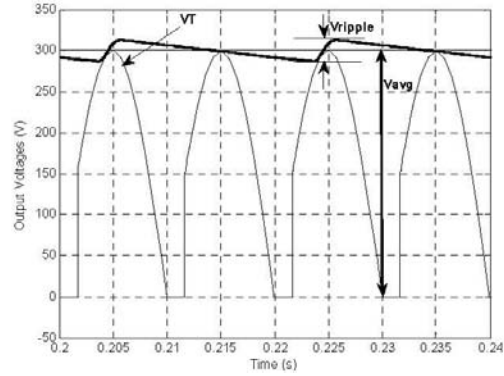


Fig. 10. Output voltages of half-controlled rectifier with LC filter.

Speed control method using half-controlled rectifier

In this case, a single phase half-controlled rectifier [19] is used to drive the motor. The half-controlled rectifier contains two diode and two silicon controlled rectifiers (SCR). The MATLAB/Simulink model of the half-controlled full wave bridge rectifier is given in Figure 7. A Pulse Generator block is used to fire the SCRs. SCR1 is triggered at a firing angle while SCR2 is triggered at a firing angle $\pi + \alpha$. The universal bridge in Figure 3 is replaced by the Simulink model of half-controlled full-wave bridge rectifier shown in Figure 7.

Similar to the full-wave bridge rectifier case, torque-speed characteristics were obtained for three different armature voltages with mean values $V_T = 180, 240$ and 300 V. The corresponding firing angles are $\alpha = 60^\circ, 45^\circ,$ and 30° . As an example, for the mean value of 300 V at $T_L = 300$ Nm input, output waveforms and the average of output voltage are in given Figure 8.

Figure 9 compares the torque-speed characteristics for the motor driven from the half-controlled

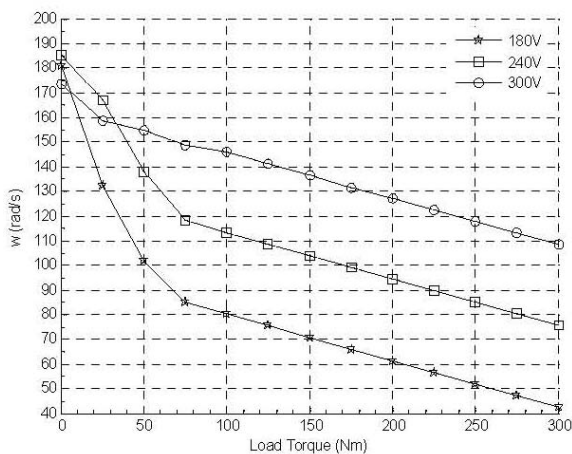


Fig. 9. Torque-speed characteristics using half-controlled rectifier.

full wave bridge rectifier without a filter. Observe that the torque-speed characteristics are highly non-linear in the light loading region of $T_L = 0 - 75$ Nm while they become linear for load $T_L > 75$ Nm. Moreover, the nonlinearity also increases when firing angle increases or the armature voltage decreases. It must be mentioned here that armature current is continuous in time in regions where the torque-speed characteristic is linear, but it is discontinuous in areas where the torque-speed characteristic is non-linear.

An LC filter is also inserted in the output terminal of half-controlled rectifier to smooth the voltage applied to the armature circuit. Figure 10 shows waveform of rectifier output with a mean value of 300 V for the load torque $T_L = 200$ Nm. As can be seen from Figure 10, the voltage applied to the armature circuit is always positive, which implies that armature current is always continuous. It is expected that such a continuous operation will remove the nonlinearity observed in the torque-speed characteristic shown in Figure 9. In fact, it is noted that the torque-speed characteristics are linear and almost the same as that for the case of full-wave bridge rectifier given in Figure 5. For that reason, they are not repeated here.

Speed control method using a PWM chopper drive

In this section, the performance of the DC motor driven from a PWM chopper drive is analyzed. Figure 11 shows the Simulink realization of this method. A gate turn-off (GTO) thyristor is used as an electronic switch and a freewheeling diode is used to solve the stored inductive energy problem in the circuit. A constant 350 V DC voltage is applied to the input of the chopper. The average value of the chopper output voltage is controlled by changing the duty ratio (D) of the PWM chopper. A pulse generator is used to change the duty ratio, and the switching frequency is initially selected as 50 Hz. The following duty ratios are used to obtain $180, 240$ and 300 V average output voltages: $D = 0.514, 0.685,$ and 0.857 .

Similar to the previous cases, torque-speed characteristics are obtained for three different armature

computations of losses, voltage regulation, efficiency, induced torque, torque-speed characteristics, etc. using per-phase equivalent circuits [17]. The latter is a control orientated electric machinery course that offers both steady-state and dynamic operation principles, and mathematical models of DC machines. For the steady-state analysis, the topics covered by the course include the structure of DC machines, equivalent circuit model, torque-speed characteristics and speed control methods by varying the field flux, the armature resistance and the armature applied voltage. In the dynamic analysis, the course covers the fundamentals of linear control theory and feedback control design, dynamic models of DC machines such as transfer function or state-space equation models, and power electronic converter based DC motor drives.

The proposed simulation models were extensively used in EEM 435 Electric Machinery II course. After the steady-state equivalent circuit model, operation principle, torque-speed characteristics, fundamentals of power electronic converters and speed control methods are covered in the class, the instructor uses Simulink models to demonstrate the effects of equivalent circuit parameters such as field resistance and armature voltage, and converter parameters such as firing angle and switching frequency on the motor speed under a wide range of loading conditions. After the demonstration, students are asked to obtain the torque-speed characteristics for each control method 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 motors, various speed control techniques and applications of various power electronic converters into DC motor speed control. Moreover, after having enough experiences with the simulation models, the following exercises are assigned to students:

- i) Using the half-controlled rectifier, obtain the plot of the motor speed in rpm vs. the arma-

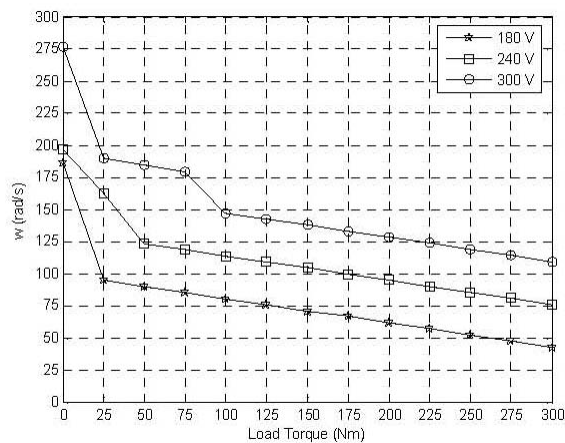


Fig. 14. Torque speed characteristics using a PWM chopper drive at 500 Hz switching frequency.

ture voltage at a given load level in a linear region of operation, say $T_L=100$ Nm and using Matlab curve fitting tool, find an equation that describes motor speed as a function of the armature voltage.

- ii) Replace the universal bridge rectifier in Fig. 3 by a fully-controlled thyristor rectifier, obtain torque-speed characteristics for various values of the firing angle, and observe how the variation in firing angle affects the linearity of the torque-speed characteristic.
- iii) Using PWM chopper drive in Fig. 11, obtain the torque-speed characteristics for the following switching frequencies: 100, 200, 300, 400, and 500 Hz; and observe how an increase in the switching frequency affects the linearity of the torque-speed characteristic and continuity of the armature current.

Examples of simulation results obtained by students for the third assignment are presented in Figures 14 and 15. Figure 14 shows torque-speed characteristics for a 500 Hz switching frequency. When compared with Figure 12, it is clear that for all voltage values, the linear region of operation extends when the switching frequency is increased. For example, the region between 0 and 175 Nm was nonlinear for 180 V armature voltage when a 50 Hz switching frequency is selected. For 500 Hz, the size of nonlinear region shrank to between 0 and 25 Nm. This is because armature current becomes continuous and smoother when the switching frequency is increased, as shown in Figure 15 for 75 Nm loading. Such simulation exercises enable students to investigate the changes in the torque-speed characteristic and armature current as the switching frequency is increased. Moreover, they can easily identify voltage and current waveforms associated with different DC motor drives and to understand how the waveforms affect the linearity of the torque-speed characteristic.

The use of the proposed simulation models was assessed both formally with student evaluations

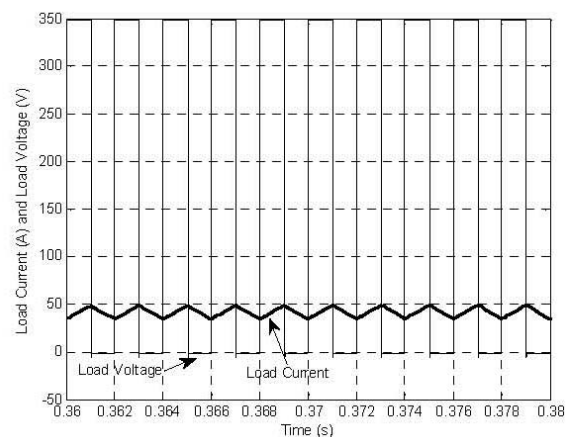


Fig. 15. Armature voltage and current wave forms at 500 Hz switching frequency.

and informally from discussions with students. Since the models were introduced to all students within a course, no good control group is available to make a meaningful statistical assessment. The student responses to the use of the models have been very positive. Their opinions can be summarized as follows:

- i) The majority of students indicate that having a tool that is easy-to-use allows them to comprehend torque-speed characteristics and speed control methods.
- ii) They appreciate that phase controlled and chopper drives significantly affect the linearity of the torque-speed characteristic.
- iii) A great deal of students feels that they increase their understanding of steady-state and dynamic behaviour of DC motors beyond the understanding they gain from classroom lectures and textbooks. Therefore, they think that simulation models complement the theoretical part of the lecture.
- iv) Most of the students believe that the use of simulation models in the classroom and in the given assignments helped them improve their exam grades.
- v) They appreciate the integrative teaching approach that combines traditional steady-state analysis of DC motors with dynamic approaches (power electronics converters) that are supported by simulation models.
- vi) Students suggest that MATLAB and Simulink/SimPowerSystems should be integrated into other power system and control courses as well.
- viii) With the extensive use of simulation models, students indicate that they have become familiar with the widely used numerical simulation environment of MATLAB and Simulink, which they will be able to use subsequently for their senior design projects or research.

CONCLUSIONS

Simulation models of power electronic converters based DC motor speed control methods have been developed using MATLAB/Simulink. Using various controlled and uncontrolled power electronic converters, torque-speed characteristics have been obtained and effects of converter parameters such as firing angle, filter and switching frequency on the linearity of the torque-speed characteristics have been thoroughly investigated. It has been shown that simulation models correctly predict the effect of the armature voltage on the torque-speed characteristics of the DC motor. It has been observed that torque-speed characteristics become linear when full-wave bridge diode rectifier (with and without a filter) and half-controlled rectifier with a filter are used to drive the motor. On the other hand, non-linear regions in the characteristics have been occurred when a half-controlled rectifier without a filter and a PWM chopper drive are used. The non-linearity is because of the discontinuity observed in the armature current. It has been also noted that the torque-speed characteristics have become more linear as the switching frequency of the PWM chopper drive is increased.

The simulation models have been successfully integrated into an undergraduate electric machinery course to enhance the teaching both the steady-state and dynamic analysis of DC motors. It has been observed that students generally find the machinery course easier to understand with hands-on experience gained through the simulated examples and they increase their understanding of fundamentals of dynamic system controls and its application into DC motor speed control, providing them a complete view of a controllable DC machine and drive systems. More importantly, such an integration results in an increase in enrollment of the machinery course.

REFERENCES

1. S. Li, and R. Chaloo, Restructuring an electric machinery course with an integrative approach and computer-assisted teaching methodology, *IEEE Trans. Educ.*, **49**(1), 2006, pp. 16–28.
2. W. M. Daniels, and A. R. Shaffer, Re-inventing the electrical machines curriculum, *IEEE Trans. Educ.*, **41**(2), 1998, pp. 92–100.
3. M. H. Nehrir, F. Fatehi, and V. Gerez, Computer modeling for enhancing instruction of electric machinery, *IEEE Trans. Educ.*, **38**(2), 1995, pp. 166–170.
4. K. A. Nigim, and R. R. DeLyser, Using MathCad in understanding the induction motor characteristics, *IEEE Trans. Educ.*, **44**(2), 2001, pp. 165–169.
5. H. A. Smolleck, Modeling and analysis of the induction machine: A computational/experimental approach, *IEEE Trans. Power Syst.*, **5**(2), 1990, pp. 482–485.
6. S. Ayasun, and C. O. Nwankpa, Induction motor test using Matlab/Simulink and their integration into undergraduate electric machinery courses, *IEEE Trans. Educ.*, **48**(1), 2005, pp. 37–46.
7. S. Ayasun, and C. O. Nwankpa, Transformer tests using MATLAB/Simulink their integration into undergraduate electric machinery courses, *Comp. App. Eng. Educ.* **14**(2), 2006, pp. 142–50.
8. S. Ayasun, and G. Karbeyaz, DC motor speed control methods using Matlab/Simulink and their integration into undergraduate electric machinery courses, *Comp. App. Eng. Educ.* **15**(4), 2007, pp. 347–54.
9. SIMULINK, Model-Based and System-Based Design, Using Simulink, MathWorks Inc., Natick, MA, (2000).
10. SimPowerSystems for Use with Simulink, User's Guide, MathWorks Inc., Natick, MA, (2002).

11. K. L. Shi, T. F. Chan, Y. K. Wong, and S. L. Ho, Modeling and simulation of the three-phase induction motor using Simulink, *Int. J. Electr. Eng. Educ.*, **36**, 1999, pp. 163–172.
12. A. Demiroren, and H. L. Zeynelgil, Modeling and simulation of synchronous machine transient analysis using SIMULINK, *Int. J. Electr. Eng. Educ.*, **39**(4), 2003, pp. 337–346.
13. C.-M. Ong, *Dynamic Simulation of Electric Machinery Using MATLAB/SIMULINK*. Upper Saddle River: Prentice Hall, (1998).
14. A. Tornambe, Analysis and synthesis in the Simulink environment of control laws for DC Motors: A real-time implementation with the microcontroller BASIC stamp II as a simple tool for an education control laboratory, *Int. J. Eng. Educ.* **21**(5), 2005, pp. 814–837.
15. D. Hercog, and K. Jezernik, Rapid control prototyping using MATLAB/Simulink and a DSP-based motor controller, *In. J. Eng. Educ.* **21**(4), 2005, pp. 596–605.
16. M. Varadarajan, and S. P. Valsan, MatPECS-A MATLAB-based power electronic circuit simulation package with GUI for effective classroom teaching, *Int. J. Eng. Educ.* **21**(4), 2005, pp. 606–611.
17. S. J. Chapman, *Electric Machinery Fundamentals*. New York: WCB/McGraw-Hill, 3rd ed., (1998).
18. D. A. Staton, M. I. McGilp, and T. J. E. Miller, DC machine teaching experiment, in *Proceedings of the European Power Electronics Association EPE*, Brighton, (1993), pp. 35–40.
19. N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics Converters, Applications and Design*. New York: John Wiley & Sons. 2nd ed, (1995).

A. Gelen received her B.Sc. degree in electrical and electronics engineering from Kahramanmaraş Sütçü İmam University, Turkey in 2003. She received her MSc. degree in electrical and electronics engineering from Nigde University, Turkey in 2006. She is currently a Ph. D. student in the same department. She has worked as a research assistant since 2004. Her research interests include power systems, power electronics, electric machinery and reactive power compensation.

S. Ayasun received his B.Sc. degree in electrical engineering from Gazi University, Ankara, Turkey, 1989, MSc degrees in electric engineering and mathematics from Drexel University, Philadelphia, PA in 1997 and 2001, respectively, and Ph.D. degree in electrical engineering from Drexel University in 2001. He is currently working as an assistant professor in the Department of Electrical and Electronics Engineering of Nigde University, Turkey. His research interests include modeling and stability analysis of dynamic systems, applied mathematics, nonlinear control theory, and bifurcation theory and its application into power systems stability analysis, the development of in-house simulation tools for undergraduate electrical engineering courses.