Electricity and New Energy

DC Motor Drives

Course Sample

8113740

Order no.: 8113740 (Printed version) 8113741 (Electronic version)
First Edition
Revision level: 09/2019

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Printed in Canada

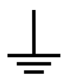
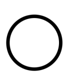
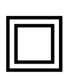
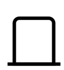
ISBN 978-2-89789-545-7 (Printed version)
ISBN 978-2-89789-546-4 (Electronic version)
Legal Deposit – Bibliothèque et Archives nationales du Québec, 2019
Legal Deposit – Library and Archives Canada, 2019

Safety and Common Symbols

The following safety and common symbols may be used in this course and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of danger. Consult the relevant user documentation.
	Caution, risk of electric shock
	Caution, lifting hazard
	Caution, hot surface
	Caution, risk of fire
	Caution, risk of explosion
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation

Safety and Common Symbols

Symbol	Description
	Consult the relevant user documentation.
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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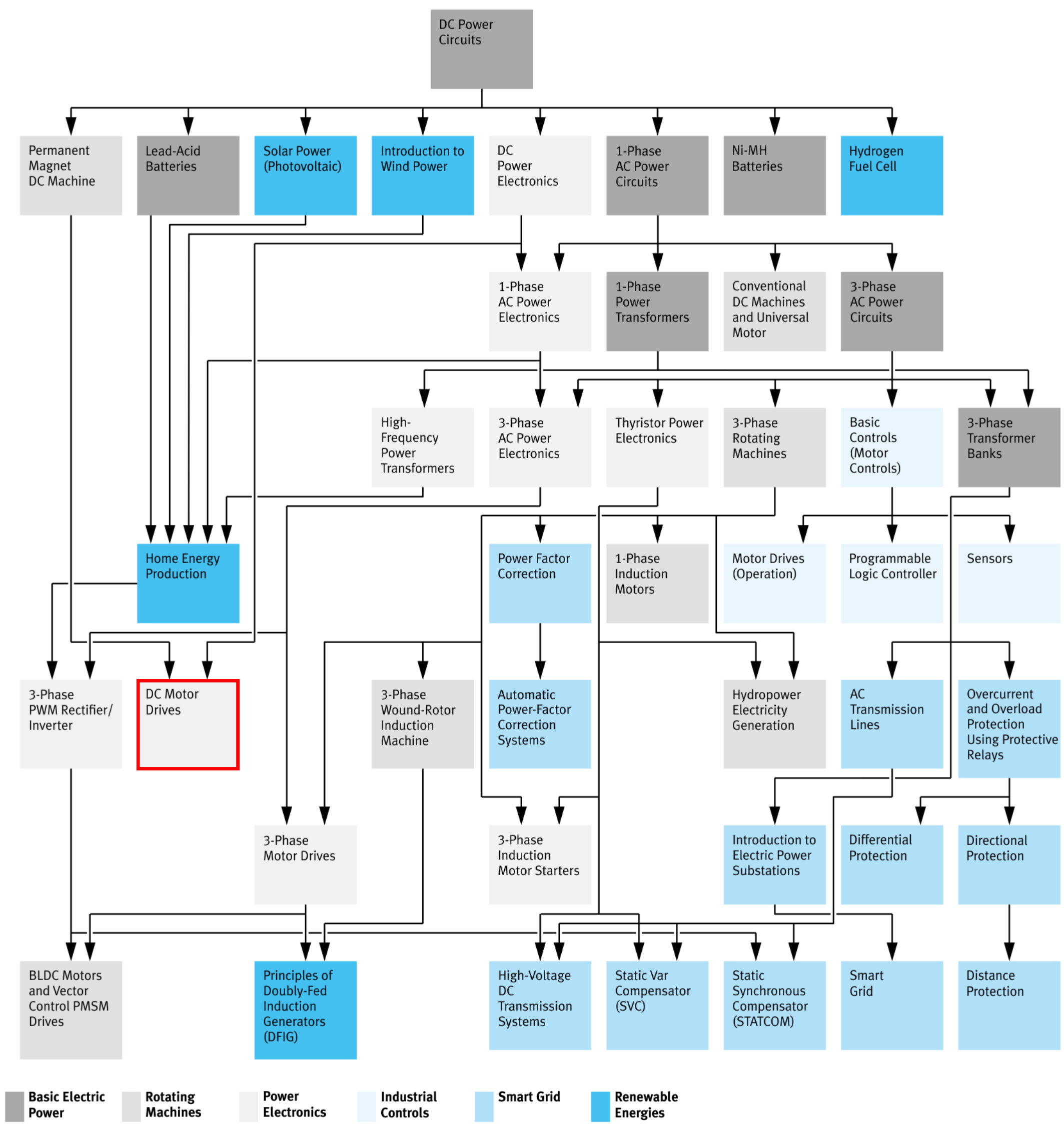
Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.



The Electric Power Technology Training Program.

Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as motor starters and drives, storage of electrical energy in batteries, home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, protective relaying, and smart-grid technologies (SVC, STATCOM, HVDC transmission systems, etc.).

We invite readers to send us their tips, feedback, and suggestions for improving the course.

Please send these to services.didactic@festo.com.

The authors and Festo Didactic look forward to your comments.

About This Course

Course objectives

This course introduces the key features of dc motor drives in a progressive way, starting with the simplest type of drive and expanding on more complex ones. Each exercise presents the features of the type of dc drive studied and the improvements gained with respect to the shortcomings of the drive studied in the previous exercise. The relevant concepts are also explained along the exercises as they become necessary.

This method allows the students to directly experiment with the different types of dc drives and to follow a structured approach to improve upon the basic PWM dc motor drive. It is our hope that this leads to a better understanding of the concepts as well as a stronger retention of the material.

Safety considerations

Safety symbols that may be used in this course and on the equipment are listed in the Safety and Common Symbols table at the beginning of this document.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Reference material

Refer to the book titled *Electric Machines, Drives, and Power Systems* written by Theodore Wildi.

For more information, you may also refer to the bibliography at the end of this course.

Prerequisite

As a prerequisite to this course, you should have completed the following courses: *DC Power Circuits*, *DC Power Electronics*, and *Permanent Magnet DC Machine*.

Systems of units

Units are expressed using the International System of Units (SI) followed by units expressed in the U.S. customary system of units (between parentheses).

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this course should be considered as a guide. Students who correctly perform the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Electric Power Technology Training Equipment must have been properly installed, according to the instructions given in the user guide Electric Power Technology Training Equipment.

Sample

Extracted from

Instructor Guide

Basic PWM DC Motor Drive

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the most basic type of PWM dc motor drive: the buck chopper dc motor drive. You will know the block diagram and the mode of operation of such a drive, as well as its main advantages and drawbacks.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Block diagram of a basic PWM dc motor drive
- Operation of a basic PWM dc motor drive
- Advantages and shortcomings of the basic PWM drive
  Advantages. Shortcomings.

DISCUSSION

Block diagram of a basic PWM dc motor drive

A basic PWM dc motor drive can be obtained by using a buck chopper to implement the power control device shown in Figure 1. The resulting circuit is shown in Figure 2. Notice that the generic dc motor can be replaced by its equivalent circuit, which consists of a resistor, an inductor, and a dc voltage source (connected in series) representing the intrinsic armature resistance (R_A), intrinsic armature inductance (L_A), and **counter-electromotive force** (E_{CEMF}) of the dc motor, respectively. In practice, the motor connected to the drive can be a conventional dc motor (separately excited or series), a permanent magnet dc motor, or a brushless dc (BLDC) motor.

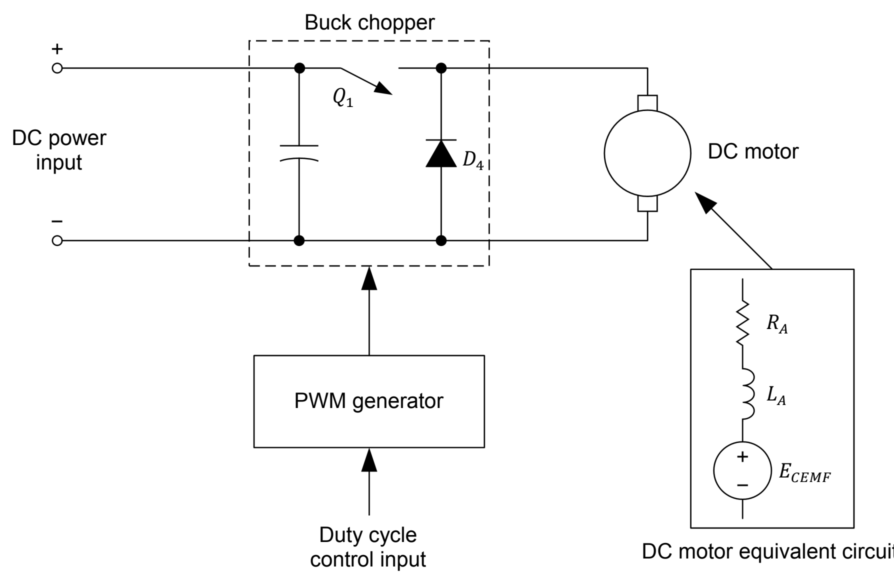


Figure 2. Basic PWM dc motor drive.

Operation of a basic PWM dc motor drive

A dc motor requires that a dc voltage be applied to its armature in order to rotate. A variable dc voltage is needed to vary the speed at which the dc motor rotates. The buck chopper provides such a variable dc voltage, whose average value depends on the duty cycle. The chopper output voltage is a fraction of the dc input voltage because its average value is proportional to the duty cycle, whose value can vary from 0 to 1. Equation (1) relates the average voltage applied to the motor armature ($E_{A,dc}$) to the dc input voltage ($E_{In,dc}$).

$$E_{A,dc} = \alpha E_{In,dc} \tag{1}$$

where α is the duty cycle of the buck chopper. It is a value between 0 and 1 (or 0% and 100%).

Figure 3 shows the motor voltage and current waveforms produced when the basic PWM dc motor drive operates at a given duty cycle. In this example, the duty cycle α is fixed to 25%. This means that the dc input voltage is applied to the dc motor armature 25% of the time. The average motor armature voltage ($E_{A,dc}$) is thus a quarter of the dc input voltage ($E_{In,dc}$).

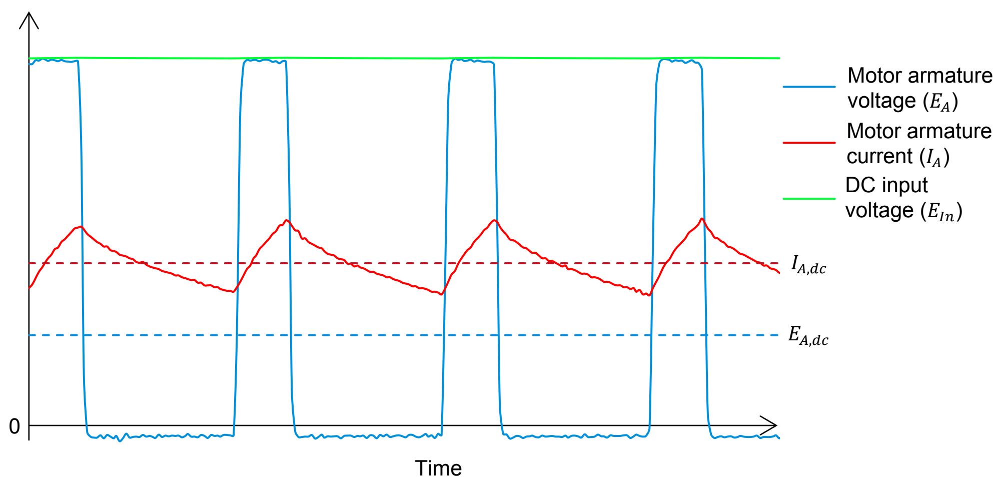


Figure 3. Motor voltage and current waveforms (α = 25%).

The armature voltage and current waveforms shown in Figure 3 are those obtained once the motor has reached its final speed for a given duty cycle. Notice how the current increases when the voltage is on (at high level) and how it decreases when the voltage is turned off (at low level). This implies that a positive current smoothed by the motor inductance (L_A) circulates through the motor.

The two possible paths taken by the armature current are shown in Figure 4. When the electronic switch is closed, the armature current (I_A) circulates from the dc source through the motor and increases as the inductance absorbs energy. When the electronic switch is open, the freewheeling diode D_4 provides a path for the armature current as the energy stored in the inductance is released to the circuit.

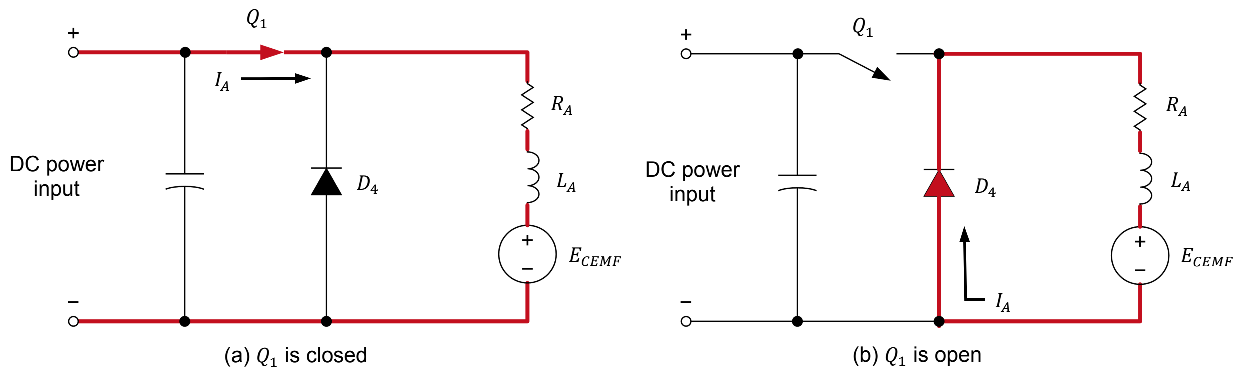


Figure 4. The two paths of the armature current.

Note, however, that the relation of Equation (1) does not always apply. Figure 5 shows that the motor armature voltage and current waveforms during deceleration differ from those obtained during steady-state operation (see Figure 3). When switch Q_1 opens, the motor armature voltage drops to virtually zero and the motor armature current decreases as the energy stored in the armature inductance (L_A) is released through diode D_4. When the current reaches zero, diode D_4 becomes blocked. At this moment, the motor armature voltage becomes equal to E_{CEMF} which is not null since the motor is still rotating due to inertia. This supplementary voltage (E_{CEMF}) increases the average motor armature voltage $E_{A,dc}$ to a value higher than that predicted by Equation (1). The motor eventually slows down to a speed corresponding to the average motor armature voltage $E_{A,dc}$ applied by the buck chopper. As the motor slows down, the plateau caused in the armature voltage waveform by the E_{CEMF} voltage decreases and eventually disappears. The duration of this process depends on the inertia of the system.

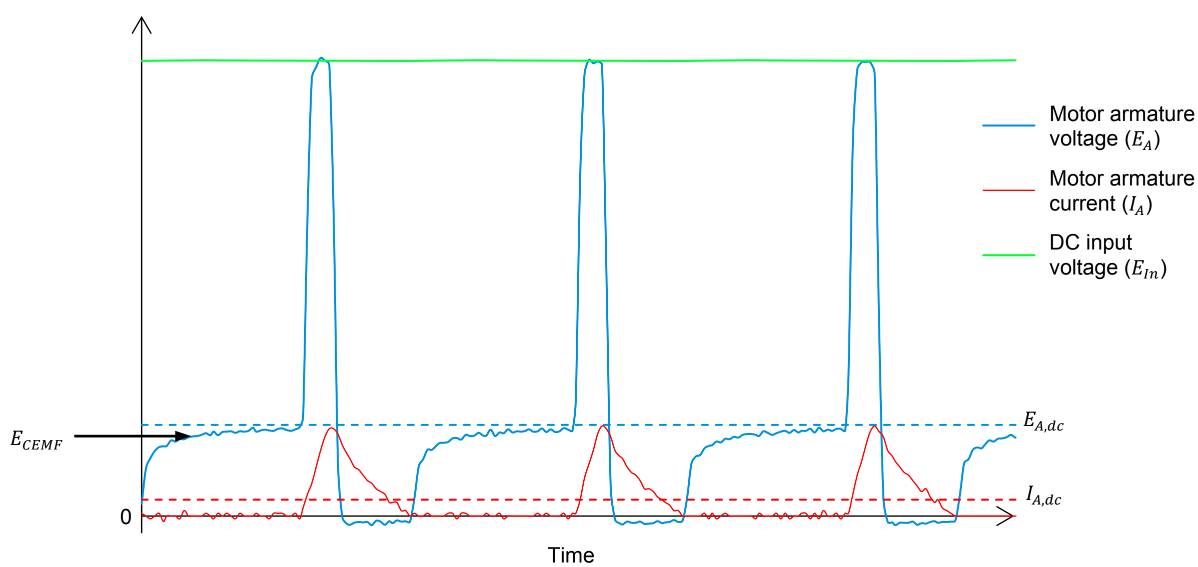


Figure 5. Voltage and current waveforms during deceleration (α is decreased to 10%).

Advantages and shortcomings of the basic PWM drive

Advantages

The basic PWM dc motor drive has the tremendous advantage of being very simple. It features few electronic components and the ones used are common. This makes its cost very low and provides high reliability. These reasons explain why basic PWM dc motor drives can still be found in many applications despite their drawbacks.

Shortcomings

The simplicity of the basic PWM dc motor drive results in the following shortcomings:

- **Poor speed regulation**: a given duty cycle of the buck chopper results in a fixed rotation speed of the motor, but only for a given mechanical load. Any change of the load torque affects the speed of rotation of the motor. Thus, the motor rotation speed is not regulated at all by the drive and it depends on the load torque and on the torque-speed characteristic of the dc motor used.

- **Unidirectional**: the buck chopper supplies unipolar dc voltage only. Because it is impossible to reverse the polarity of the dc voltage applied to the motor armature, the motor can rotate in one direction only. This can be problematic in many applications.

- **Coasting** during decelerations: when the motor is already rotating at a given speed, reducing the duty cycle causes the motor to slow down to a certain speed at a rate proportional to the forces (torque) opposing motor rotation and inversely proportional to the system inertia. During the time the motor slows down, the drive loses control on the rotation speed of the motor. This is not acceptable in applications requiring tight control of the motor speed.

- **Overcurrent** during acceleration: whenever the chopper duty cycle is increased significantly to increase the motor speed, the motor armature current can increase greatly during the acceleration. When the increase is such that the nominal armature current of the motor is exceeded for a sufficiently long time, the overload protection circuit trips (damage to the motor is likely if the motor does not possess a protection circuit). All of this, obviously, can be highly problematic.

All the shortcomings presented above will be discussed further and corrected in the next two exercises of this course.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Operation of the basic PWM dc motor drive
- Motor coasting
- Motor overcurrents during acceleration
- Effects of the mechanical load on the motor speed

PROCEDURE

⚠ WARNING

High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

Set up and connections

In this part of the exercise, you will set up and connect the equipment.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform the exercise.

   Install the equipment in the Workstation.

   Make sure that the Permanent Magnet DC Machine is installed on the right of the Four-Quadrant Dynamometer/Power Supply.

   Before performing this exercise, measure the open-circuit voltage across the Lead-Acid Battery Pack, using a multimeter. If the open-circuit voltage is lower than 51.2 V, ask your instructor for assistance as the Lead-Acid Battery Pack is probably not fully charged. Appendix D indicates how to fully charge the Lead-Acid Battery Pack before a lab period.

> Notice that the term IGBT is used throughout this course when referring to the IGBT Chopper/Inverter module.

2. Mechanically couple the Permanent Magnet DC Machine to the Four-Quadrant Dynamometer/Power Supply using the timing belt.

⚠ WARNING

Before coupling rotating machines or working on them, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

3. Make sure that the main power switch on the Four-Quadrant Dynamometer/Power Supply is set to the *O* (off) position, then connect its *Power Input* to an ac power wall outlet.

4. Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to a 24 V ac power supply.

   Connect the *Low Power Input* of the Chopper/Inverter to the *Power Input* of the DACI. Turn the 24 V ac power supply on.

5. Connect the USB port of the DACI to a USB port of the host computer.

Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

6. Turn the Four-Quadrant Dynamometer/Power Supply on, then set the *Operating Mode* switch to *Dynamometer*.

7. Turn the host computer on, then start the LVDAC-EMS software.

In the LVDAC-EMS Start-Up window, make sure that the DACI and the Four-Quadrant Dynamometer/Power Supply are detected.

Make sure that the *Computer-Based Instrumentation* and *Chopper/Inverter Control* functions for the DACI are available. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

8. Connect the *Digital Outputs* of the DACI to the *Switching Control Inputs* of the Chopper/Inverter using a DB9 connector cable.

On the Chopper/Inverter, set the *Dumping* switch to the *O* (off) position. The *Dumping* switch is used to prevent overvoltage on the dc bus of the Chopper/Inverter. It is not required in this exercise.

9. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window. In the *Tools* menu of this window, select *Friction Compensation Calibration*, which will bring up the Friction Compensation Calibration dialog box. Click *OK* in this box to start the calibration process. Observe that the prime mover starts to rotate at high speed, thereby driving the Permanent Magnet DC Machine. The prime mover speed is then automatically decreased by steps to perform the calibration process. Once the calibration process is completed (which takes about five minutes), the prime mover stops rotating, then the Friction Compensation Calibration dialog box indicates that the calibration process is finished. Click *OK* in the Friction Compensation Calibration dialog box to close this box and apply the changes (i.e., the newly calibrated friction compensation).

10. Set up the circuit shown in Figure 6. Use the Lead-Acid Battery Pack as a fixed-voltage dc power source for the basic PWM dc motor drive.

Since the Permanent Magnet DC Machine operates as a dc motor, it will be referred to as “dc motor” or simply “motor” for the rest of the exercise.

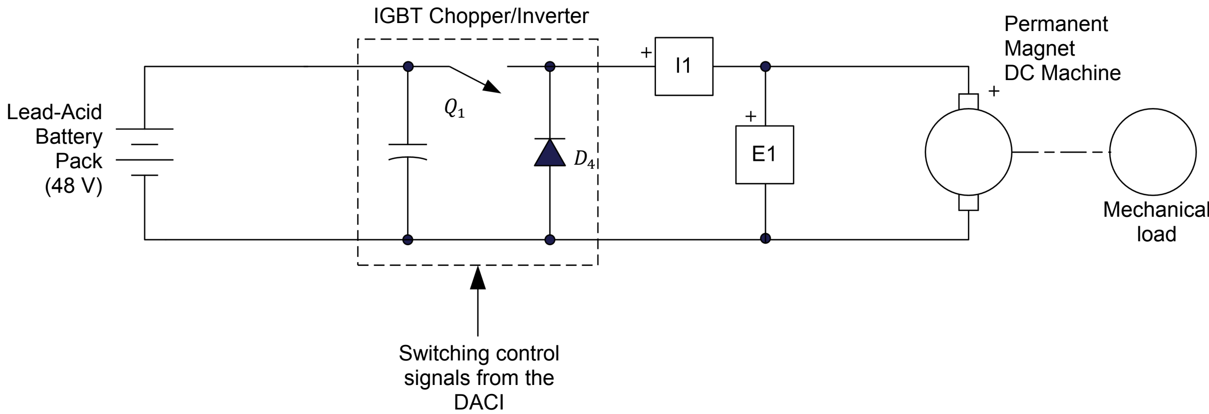


Figure 6. Basic PWM dc motor drive (buck chopper dc motor drive).

11. In LVDAC-EMS, open the Chopper/Inverter Control window, then make the following settings:

- Set the *Function* parameter to *Buck Chopper (High-Side Switching)*.
- Set the *Switching Frequency* parameter to 12 kHz.

A typical switching frequency for a buck chopper is around 20 kHz. The switching frequency is set to 12 kHz in this exercise to allow observation of the motor voltage and current waveforms using the Oscilloscope without aliasing effect and without having too much audible noise.

12. In the Four-Quadrant Dynamometer/Power Supply window, make the following settings:

- Set the *Function* parameter to *Mechanical Load*. This makes the Four-Quadrant Dynamometer/Power Supply operate like a configurable mechanical load.
- Set the *Load Type* parameter to *Flywheel*. This makes the mechanical load emulate a flywheel.
- Set the *Inertia* parameter to 0.025 kg·m^2 (0.593 lb·ft^2). This sets the inertia of the emulated flywheel.
- Set the *Friction Torque* parameter to 0.20 N·m (1.77 lbf·in). This sets the torque which opposes rotation of the emulated flywheel.
- Set the *Pulley Ratio* parameter to 24:12.

Note that the pulley ratio between the Four-Quadrant Power Supply/Dynamometer and the Permanent Magnet DC Machine is 24:12.

Start the mechanical load. The Permanent Magnet DC Machine (i.e., the dc motor) is now coupled to a flywheel emulated by the mechanical load.

Operation of the basic PWM dc motor drive

In this part of the exercise, you will use the basic PWM dc motor drive to power the dc motor. You will observe the behavior (armature voltage and speed) of the dc motor as the duty cycle of the buck chopper is changed.

13. In LVDAC-EMS, open the Metering window. Set three meters to measure the dc motor armature voltage (input *E1*), the armature current (input *I1*), and electrical power (measured from inputs *E1* and *I1*).

Click the *Continuous Refresh* button to enable continuous refresh of the values indicated by the various meters in the Metering window.

Note that you can observe the dc motor speed, torque, and mechanical power in the Four-Quadrant Dynamometer/Power Supply window.

14. In LVDAC-EMS, open the Oscilloscope window. Make the appropriate settings to observe the waveforms of the dc motor armature voltage and armature current (inputs *E1* and *I1*, respectively).

Click the *Continuous Refresh* button to enable continuous display refresh of the waveforms shown in the Oscilloscope window.

15. In LVDAC-EMS, open the Data Table window. Set the data table to record the duty cycle of the buck chopper, as well as the dc motor armature voltage and speed.

16. In the Chopper/Inverter Control window, start the buck chopper (i.e., the basic PWM dc motor drive) by clicking the *Start/Stop* button. Increase the duty cycle of the buck chopper from 0% to 100% in 10% steps while observing the measured values of the motor armature voltage, armature current, speed, and torque, as well as the motor armature voltage and current waveforms. For each duty cycle value, record in the data table the duty cycle of the buck chopper, as well as the motor armature voltage and speed.

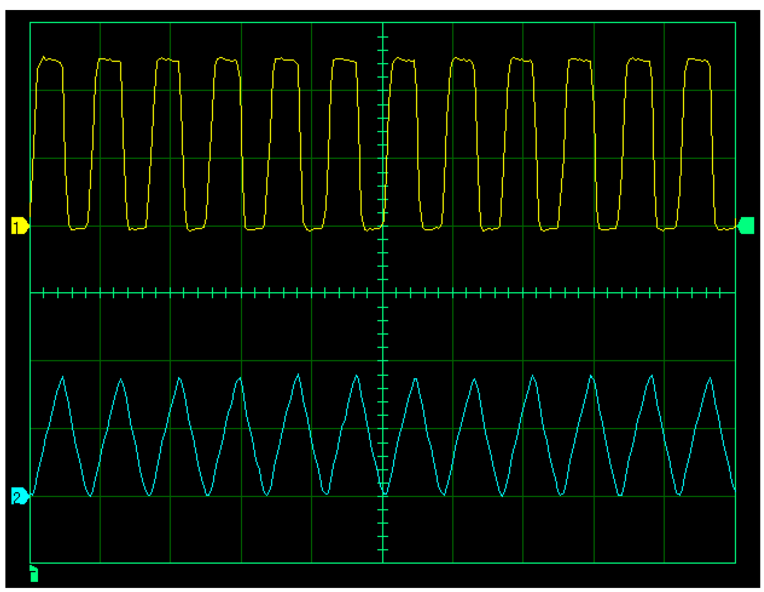
The results are presented in the following table.

Armature voltage and speed of the dc motor as a function of the duty cycle of the buck chopper.

Duty cycle α (%)	Motor armature voltage (V)	Motor speed (r/min)
0	0.018	0
10	4.06	314
20	8.90	688
30	14.0	1132
40	19.2	1574
50	24.8	2052
60	29.6	2444
70	34.2	2830
80	39.2	3266
90	44.2	3692
100	49.5	4142

Typical waveforms for the motor armature voltage and current (duty cycle α = 50%) are shown below.

Oscilloscope Settings:
Channel 1 Input E1
Channel 1 Scale ....20 V/div
Channel 2 Input I1
Channel 2 Scale ....1.0 A/div
Time Base..........................0.1 ms/div
Trigger Source .... Ch 1
Trigger Level................................. 0 V
Trigger Slope ....Rising



Waveforms of the motor armature voltage and current when operating at α = 50%.

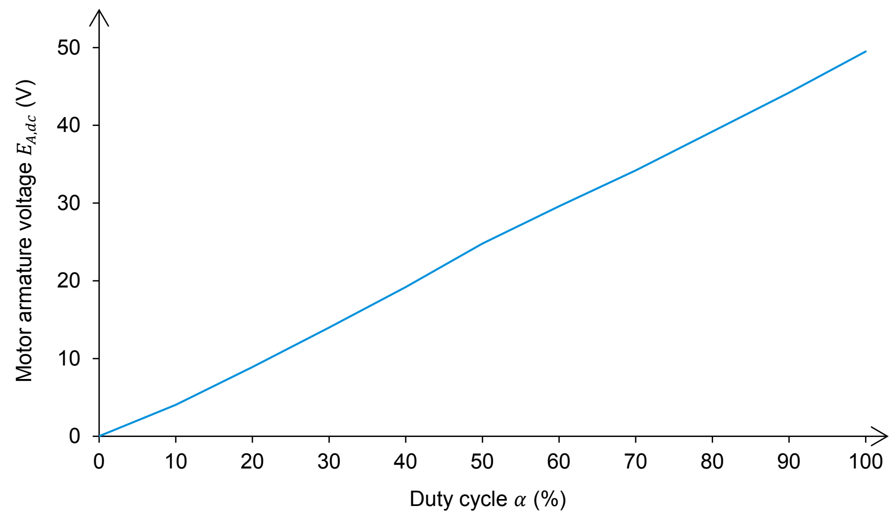
17. In the Chopper/Inverter Control window, stop the basic PWM dc motor drive.

In the Four-Quadrant Dynamometer/Power Supply window, stop the mechanical load (i.e., the emulated flywheel).

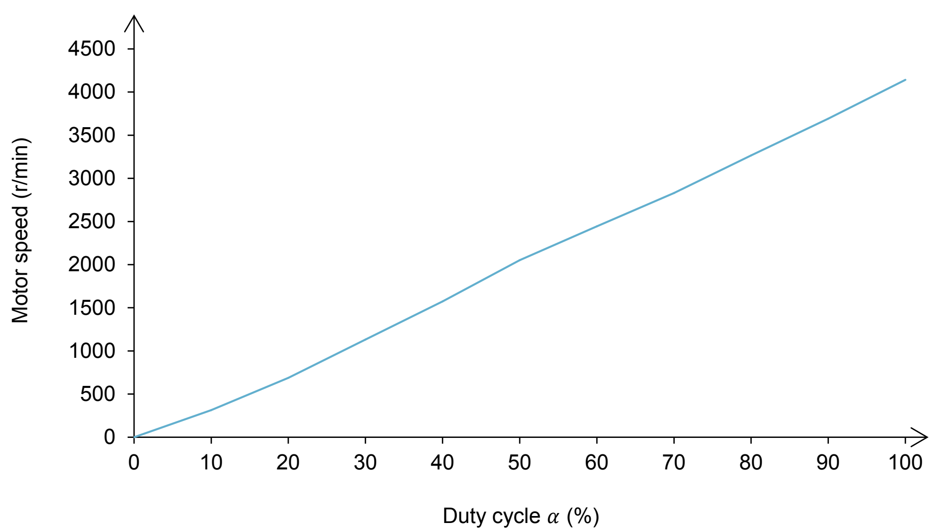
18. Plot on a graph the relationship between the armature voltage ($E_{A,dc}$) of the dc motor and the duty cycle α of the buck chopper.

Plot on a second graph the relationship between the speed of the dc motor and the duty cycle α of the buck chopper.

The resulting graphs are shown below.



Armature voltage ($E_{A,dc}$) of the dc motor as a function of the duty cycle α of the buck chopper.



Speed of the dc motor as a function of the duty cycle α of the buck chopper.

What is the relationship between the armature voltage ($E_{A,dc}$) of the dc motor and the duty cycle α of the buck chopper?

The armature voltage $E_{A,dc}$ of the dc motor increases linearly from 0 to the maximum value (≅ 48 V) when the duty cycle α of the buck chopper passes from 0% to 100%.

What is the relationship between the speed of the dc motor and the duty cycle α of the buck chopper?

The speed of the dc motor increases linearly from 0 to the maximum value (≅ 4140 r/min) when the duty cycle α of the buck chopper passes from 0% to 100%.

Is it possible to make the dc motor rotate in both directions? Explain briefly.

No, because the polarity (positive) of the dc motor armature voltage remains the same over the complete range of duty cycle values (0% to 100%).

19. Briefly describe the operation of the basic PWM dc motor drive based on the armature voltage and current waveforms observed, and on the two graphs plotted in step 18.

The dc voltage ($E_{A,dc}$) applied to the dc motor armature increases linearly as the duty cycle α of the buck chopper is increased. Consequently, the motor speed increases linearly with the duty cycle. The armature voltage waveform is a rectangular pulse wave, the pulse width being determined by the duty cycle. On the other hand, the armature current waveform is more like a triangle wave due to the smoothing action of the dc motor armature inductance.

Motor coasting

In this part of the exercise, you will use the basic PWM dc motor drive to power the dc motor. You will observe the motor's behavior during deceleration as the parameters of the simulated load are changed.

20. Modify the equipment connection so as to use the 40 A terminal of current input *I1* of the DACI instead of the 4 A terminal. Set the range of current input *I1* to *High (40 A)* in the Data Acquisition and Control Settings window of LVDAC-EMS.

21. In the Four-Quadrant Dynamometer/Power Supply window, make the following settings:

– Set the *Inertia* parameter of the emulated flywheel to 0.100 kg·m^2 (2.373 lb·ft^2).

– Set the *Friction Torque* parameter of the emulated flywheel to 0.30 N·m (2.66 lbf·in).

Start the mechanical load (i.e., the emulated flywheel).

22. In the Chopper/Inverter Control window, start the basic PWM dc motor drive and **slowly** increase the duty cycle of the buck chopper from 0% to 60%. Let the dc motor speed stabilize.

Increasing the duty cycle in large increments might cause an overcurrent condition to happen in the IGBT Chopper/Inverter module. If this occurs, stop the drive, set the duty cycle to 0%, press the Overcurrent Reset *button on the IGBT Chopper/Inverter module, and redo the manipulation using smaller duty cycle increments.*

23. Suddenly decrease the duty cycle from 60% to 40% while observing the measured values of the dc motor speed, torque, mechanical power, armature voltage, armature current, and electrical power, as well as the armature voltage and current waveforms. Notice that the counter-electromotive force (E_{CEMF}) appears in the armature voltage waveform when the duty cycle is decreased suddenly to decrease the motor speed, because the armature current momentarily decreases to zero. This is shown in Figure 7.

Oscilloscope Settings:
Channel 1 Input E1
Channel 1 Scale .... 20 V/div
Channel 2 Input I1
Channel 2 Scale .... 2 A/div
Time Base .... 0.1 ms/div
Trigger Source .... Ch 1
Trigger Level .... 0 V
Trigger Slope .... Rising

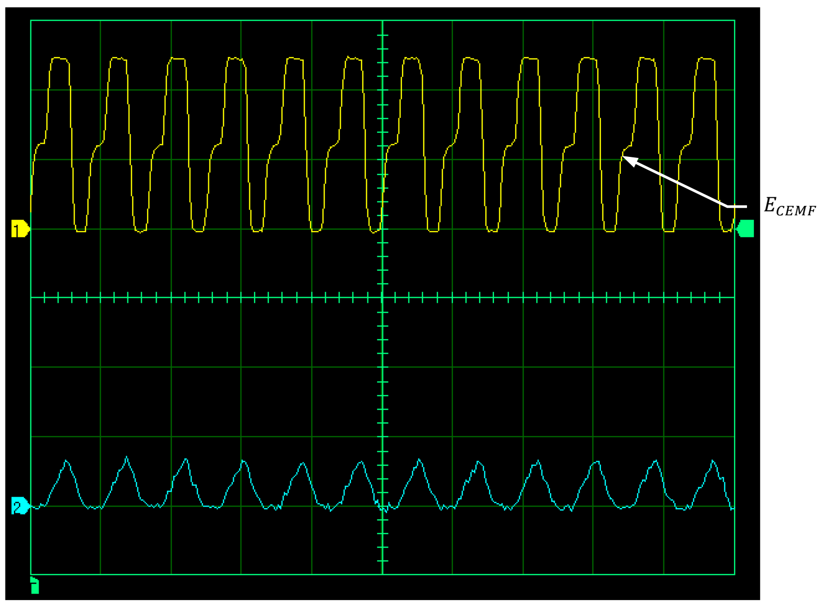


Figure 7. The dc motor counter-electromotive force (E_{CEMF}) is visible in the armature voltage waveform during the deceleration.

What happens to the motor speed and motor counter-electromotive force (E_{CEMF}) after the duty cycle of the buck chopper is decreased suddenly?

The motor speed decreases slowly (i.e., the motor coasts) until it settles to a new steady-state value (i.e., the operating speed corresponds to the new duty cycle value). Also, the E_{CEMF} voltage decreases in sync with the speed, until it disappears when the motor armature current reaches zero.

Why does it take some time for the motor speed to settle to a steady-state value?

Because the inertia of the load is relatively large and the friction torque opposing rotation is small. Little force opposes motor rotation (T_{Motor} and P_M are close to zero). Consequently, the motor speed decreases very slowly.

Is control of the motor speed (via a change of the duty cycle) efficient during deceleration? Why?

No. There is a loss of control of the motor speed as the motor coasts to its new speed during deceleration. This is due to the fact that the basic PWM dc motor drive does not have any braking capabilities.

24. In the Data Table window, set the timer to make 300 records with an interval of 1 second between each record. This corresponds to a 5-minute period.

Set the data table to record the dc motor speed and armature current, as well as the chopper duty cycle. Also, set the data table to record the time associated with each record.

Start the timer to begin recording data.

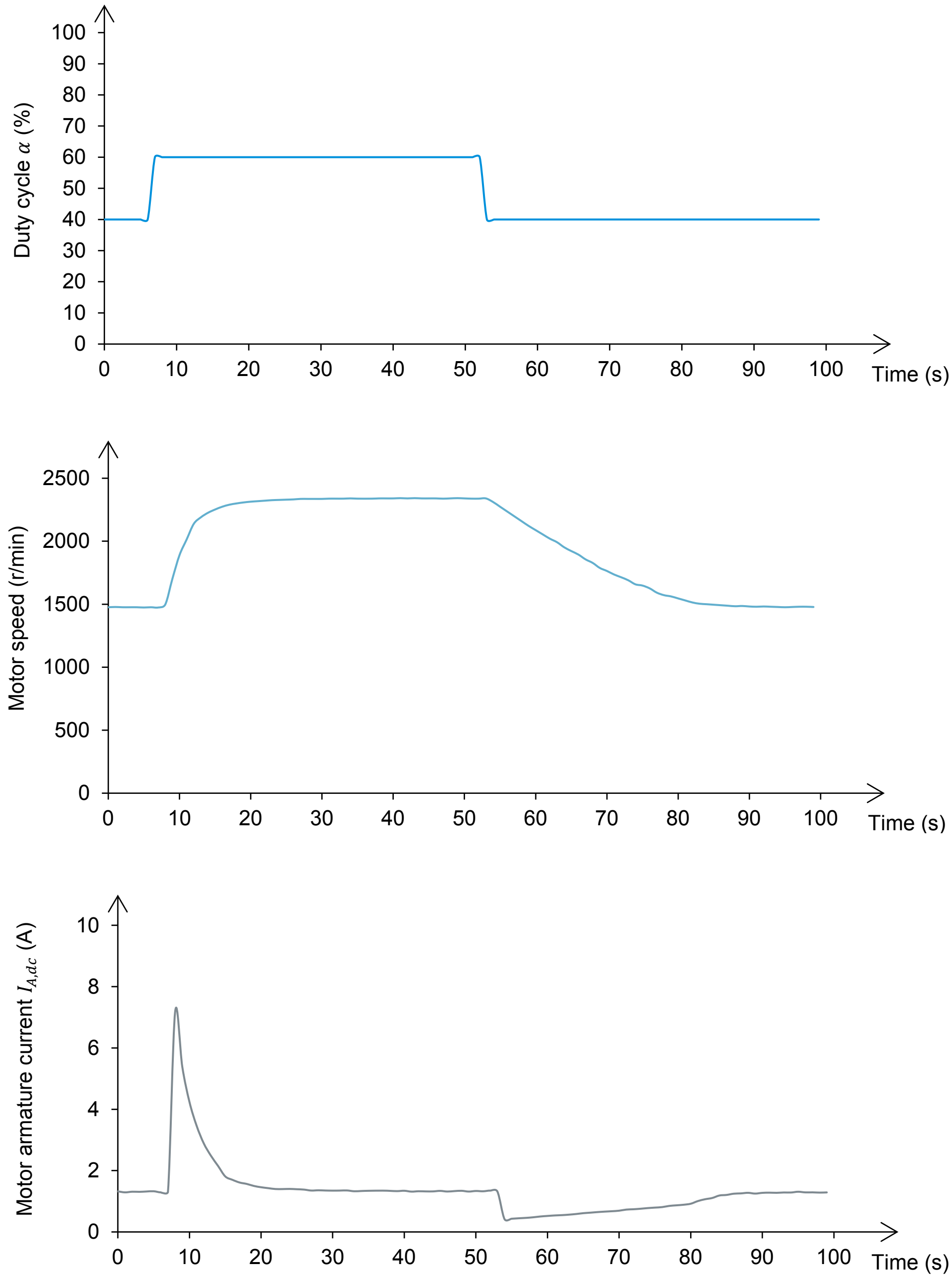
25. Suddenly increase the duty cycle of the buck chopper from 40% to 60% and wait for the motor speed to stabilize. Once the motor speed has stabilized, suddenly decrease the duty cycle from 60% to 40%. Wait again for the motor speed to stabilize.

In the Data Table window, stop the timer, then save the recorded data.

In the Chopper/Inverter Control window, set the buck chopper duty cycle to 0%, then stop the basic PWM dc motor drive. In the Four-Quadrant Dynamometer/Power Supply window, stop the mechanical load (i.e., the emulated flywheel). Wait until the motor stops.

26. Plot graphs showing the evolution of the chopper duty cycle, motor speed, and motor armature current as a function of time using the data you saved. Observe the evolution of the different parameters.

The resulting graphs are shown below.



Graphs of the duty cycle, motor speed, and motor armature current as a function of time. [Inertia: 0.100 kg·m^2 (2.373 lb·ft^2), friction torque: 0.30 N·m (2.66 lbf·in)].

What is the motor deceleration time (i.e., the time required to reach steady-state motor speed when the duty cycle is decreased to 40%)?

The deceleration time is 43 s when the flywheel inertia is 0.100 kg·m^2 (2.373 lb·ft^2) and the friction torque is 0.30 N·m (2.66 lbf·in).

What value does the motor armature current ($I_{A,dc}$) reach during the motor acceleration?

The motor armature current ($I_{A,dc}$) reaches a value of about 7 A during the motor acceleration when the flywheel inertia is 0.100 kg·m^2 (2.373 lb·ft^2) and the friction torque is 0.30 N·m (2.66 lbf·in).

27. In the Four-Quadrant Dynamometer/Power Supply window, set the inertia of the emulated flywheel to half its present value, i.e., set the *Inertia* parameter to 0.050 kg·m^2 (1.187 lb·ft^2). Start the mechanical load (i.e., the emulated flywheel).

In the Chopper/Inverter Control window, start the basic PWM dc motor drive and progressively increase the duty cycle of the buck chopper to 40%. Wait for the motor speed to stabilize.

In the Data Table window, clear all the recorded data without modifying the record and timer settings. Start the timer to begin recording data.

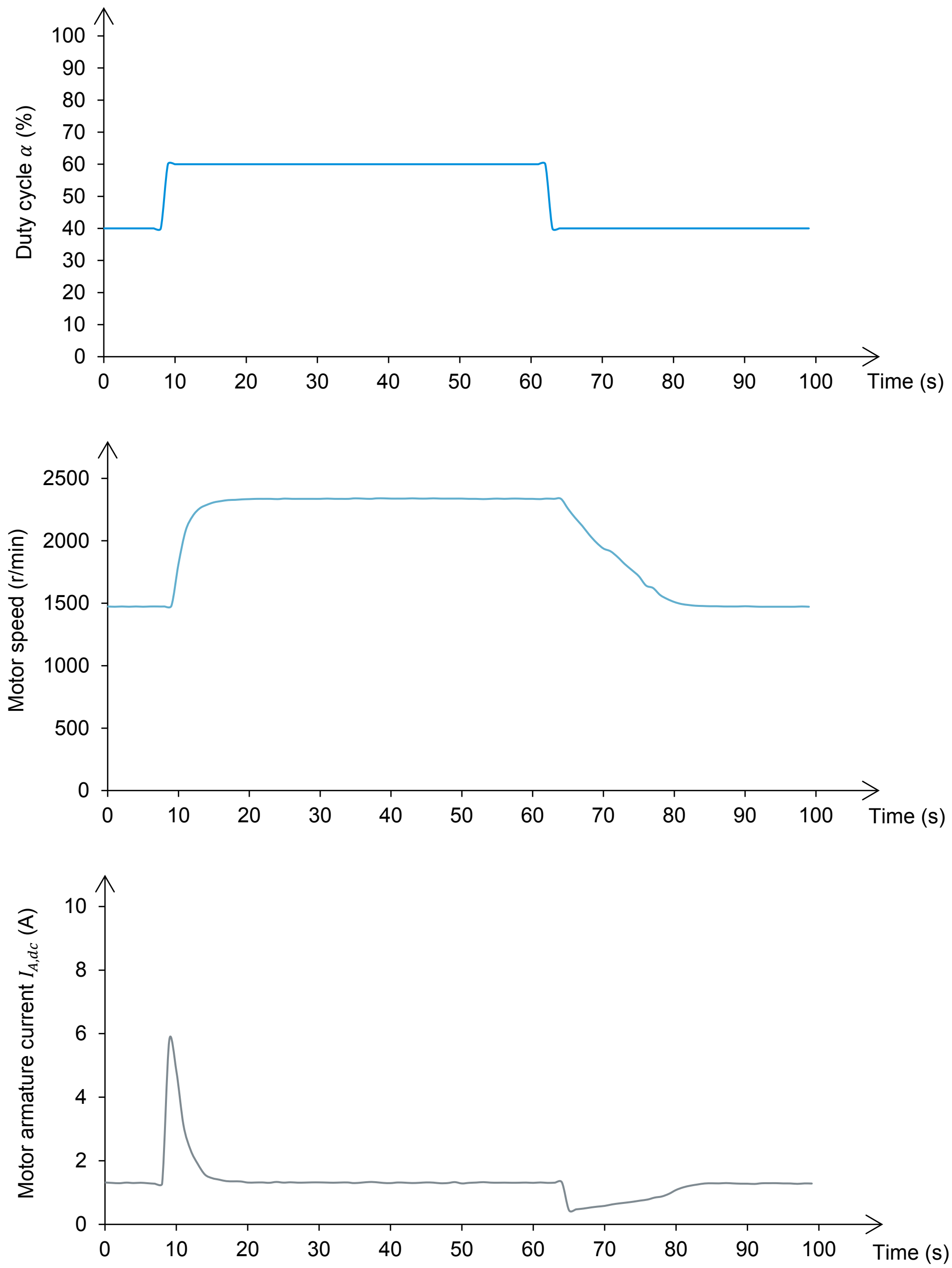
28. In the Chopper/Inverter Control window, suddenly increase the buck chopper duty cycle from 40% to 60%. Once the motor speed has stabilized, suddenly decrease the duty cycle from 60% to 40%. Wait for the motor speed to stabilize.

In the Data Table window, stop the timer, then save the recorded data.

In the Chopper/Inverter Control window, set the buck chopper duty cycle to 0%, then stop the basic PWM dc motor drive. On the Four-Quadrant Dynamometer/Power Supply window, stop the mechanical load (i.e., the emulated flywheel). Wait until the motor stops.

29. Plot graphs showing the evolution of the chopper duty cycle, motor speed, and motor armature current as a function of time using the data you saved. Observe the evolution of the different parameters.

The resulting graphs are shown below.



Graphs of the duty cycle, motor speed, and motor armature current as a function of time [Inertia: 0.050 kg·m^2 (1.187 lb·ft^2), friction torque: 0.30 N·m (2.66 lbf·in)].

What is the motor deceleration time when the inertia of the load is decreased by two? How does it compare to the deceleration time obtained earlier when the inertia of the flywheel was twice the present value?

The motor deceleration time when the flywheel inertia is 0.050 kg·m^2 (1.187 lb·ft^2) and the friction torque is 0.30 N·m (2.66 lbf·in) is 22 s. This deceleration time is approximately half the value measured earlier when the flywheel inertia was 0.100 kg·m^2 (2.373 lb·ft^2).

What is the relationship between the motor deceleration time (i.e., the motor coasting time) and the inertia of the load?

The motor deceleration time (coasting time) is directly proportional to the inertia of the load.

What value does the motor armature current ($I_{A,dc}$) reach during the motor acceleration?

The motor armature current ($I_{A,dc}$) reaches a value of about 6 A during the motor acceleration when the flywheel inertia is 0.050 kg·m^2 (1.187 lb·ft^2) and the friction torque is 0.30 N·m (2.66 lbf·in).

30. In the Four-Quadrant Dynamometer/Power Supply window, set the inertia of the emulated flywheel back to its original value of 0.100 kg·m^2 (2.373 lb·ft^2), then increase its friction torque to 0.60 N·m (5.31 lbf·in). Start the mechanical load (i.e., the emulated flywheel).

In the Chopper/Inverter Control window, start the basic PWM dc motor drive and progressively increase the duty cycle of the buck chopper to 40%. Wait for the motor speed to stabilize.

In the Data Table window, clear all the recorded data without modifying the record and timer settings. Start the timer to begin recording data.

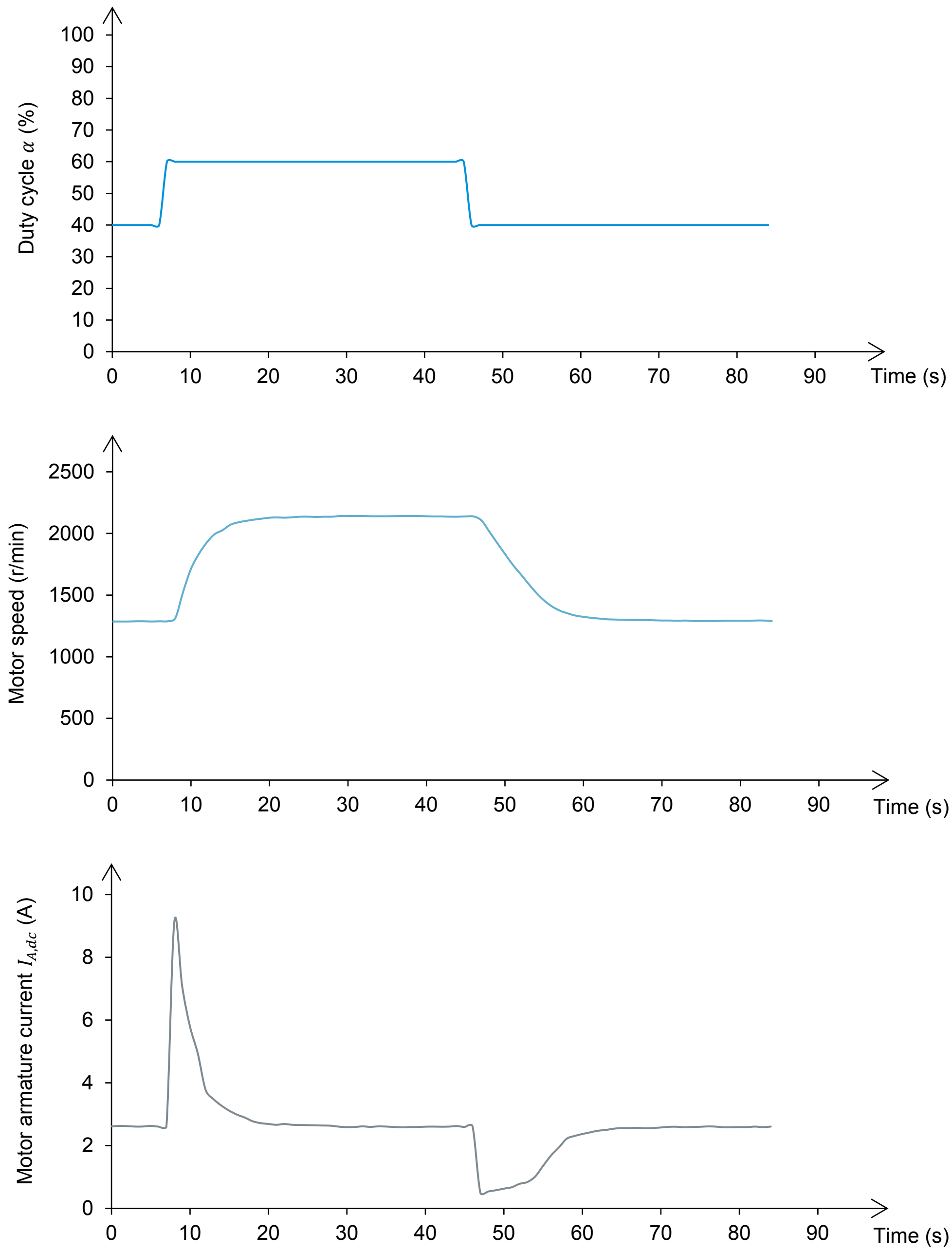
31. In the Chopper/Inverter Control window, suddenly increase the buck chopper duty cycle from 40% to 60%. Once the motor speed has stabilized, suddenly decrease the duty cycle from 60% to 40%. Wait for the motor speed to stabilize.

In the Data Table window, stop the timer, then save the recorded data.

In the Chopper/Inverter Control window, set the buck chopper duty cycle to 0%, then stop the basic PWM dc motor drive. In the Four-Quadrant Dynamometer/Power Supply window, stop the mechanical load (i.e., the emulated flywheel). Wait until the motor stops.

32. Plot graphs showing the evolution of the chopper duty cycle, motor speed, and motor armature current as a function of time using the data you saved. Observe the evolution of the different parameters.

The resulting graphs are shown below.



Graphs of the duty cycle, motor speed, and motor armature current as a function of time [Inertia: 0.100 kg·m^2 (2.373 lb·ft^2), friction torque: 0.60 N·m (5.31 lbf·in)].

What is the motor deceleration time? How does it compare to the motor deceleration time measured in step 26 when the flywheel inertia had the same value [i.e., 0.100 kg·m^2 (2.373 lb·ft^2)] but the friction torque had a much lower value [0.30 N·m (2.66 lbf·in)]?

The deceleration time when the flywheel inertia is 0.100 kg·m^2 (2.373 lb·ft^2) and the friction torque is 0.60 N·m (5.31 lbf·in) is 23 s. This deceleration time is about 2 times shorter than the deceleration time measured earlier when the flywheel inertia was the same [0.100 kg·m^2 (2.373 lb·ft^2)] and the friction torque was 0.30 N·m (2.66 lbf·in), i.e., half the present friction torque value [0.60 N·m (5.31 lbf·in)].

What is the relationship between the motor deceleration time (i.e., the motor coasting time) and the friction torque of the load?

The motor deceleration time (coasting time) is inversely proportional to the friction torque of the load.

What value does the motor armature current ($I_{A,dc}$) reach during the motor acceleration?

The motor armature current ($I_{A,dc}$) reaches a value of about 9 A during the motor acceleration when the flywheel inertia is 0.100 kg·m^2 (2.373 lb·ft^2) and the friction torque is 0.60 N·m (5.31 lbf·in).

Motor overcurrents during acceleration

In this part of the exercise, you will compare the maximum armature currents reached during acceleration for different inertia and friction torque values.

33. Compare the maximum values of armature current $I_{A,dc}$ measured during motor acceleration in steps 26, 29, and 32 to the nominal armature current indicated on the front panel of the Permanent Magnet DC Machine.

The maximum values of armature current $I_{A,dc}$ measured during motor acceleration usually exceeds the nominal armature current indicated on the front panel of the Permanent Magnet DC Machine.

Can this be problematic? Explain briefly.

Yes, since the overload protection circuit would trip for longer durations of the current spikes. Damage to the motor could also occur if the motor did not possess this protection circuit.

Effects of the mechanical load on the motor speed

The motor speeds measured for different values of the friction torque are compared in this part of the exercise.

34. In the Four-Quadrant Dynamometer/Power Supply window, set the inertia of the emulated flywheel to 0.025 kg·m^2 (0.593 lb·ft^2) and set its friction torque to 0.10 N·m (0.89 lbf·in). Start the mechanical load (i.e., the emulated flywheel).

In the Chopper/Inverter Control window, start the basic PWM dc motor drive and progressively increase the duty cycle of the buck chopper to 50%. Wait for the motor speed to stabilize and note its value below.

Speed of the motor [torque = 0.10 N·m (0.89 lbf·in)] = _______ r/min

Increase the friction torque of the flywheel to 0.30 N·m (2.66 lbf·in). Wait for the motor speed to stabilize and note its value:

Speed of the motor [torque = 0.30 N·m (2.66 lbf·in)] = _______ r/min

Increase the friction torque of the flywheel to 0.50 N·m (4.43 lbf·in). Wait for the motor speed to stabilize and note its value:

Speed of the motor [torque = 0.50 N·m (4.43 lbf·in)] = _______ r/min

The resulting speeds should be close to the following values:

Speed of the motor [torque = 0.10 N·m (0.89 lbf·in)] = 2594 r/min

Speed of the motor [torque = 0.30 N·m (2.66 lbf·in)] = 1880 r/min

Speed of the motor [torque = 0.50 N·m (4.43 lbf·in)] = 1752 r/min

In the Chopper/Inverter Control window, set the buck chopper duty cycle to 0% then stop the basic PWM dc motor drive. In the Four-Quadrant Dynamometer/Power Supply window, stop the mechanical load (i.e., the emulated flywheel). Wait until the motor stops.

Does the basic PWM dc motor drive provide good speed regulation? Explain briefly.

No. Speed regulation is rather poor when using a basic PWM dc motor drive. The motor speed is dependent upon the mechanical load (friction torque) applied to the motor and the drive has no way to compensate for this.

35. In the *Tools* menu of the Four-Quadrant Dynamometer/Power Supply window, select *Reset to Default Friction Compensation*. This brings up the Reset Friction Compensation dialog box. Click *Yes* in this box to reset the friction compensation to the factory default compensation.

36. Close LVDAC-EMS, then turn off all equipment. Remove all leads and cables.

Make sure the Lead-Acid Battery Pack is recharged as soon as possible.

CONCLUSION

This exercise presented the most basic type of dc motor drive available. Such a basic drive is made with a buck chopper and allows the rotation speed of a dc motor to be controlled. You learned that this type of drive features the following drawbacks: it is unidirectional, it tends to coast during deceleration, it has poor speed regulation, and it offers no protection against overcurrents occurring at the dc motor armature. You also learned that the dc motor coasting time is proportional to the inertia of the load and inversely proportional to the friction torque of the load.

The next exercises will explore methods to circumvent the different drawbacks of the basic PWM dc motor drive.

REVIEW QUESTIONS

1. To increase the average voltage at the output of a basic PWM dc motor drive, should you reduce or increase the buck chopper duty cycle? Explain why.

The duty cycle of the buck chopper should be increased. This will cause the voltage at the output of the PWM dc motor drive to be applied for a longer time every PWM cycle, thereby resulting in a larger average output voltage.

2. State an advantage of the basic PWM dc motor drive.

It is very simple, thus reliable and inexpensive.

3. The inertia of the mechanical load coupled to the dc motor in a basic PWM dc motor drive is doubled. What happens to the coasting time during any motor deceleration?

The coasting time also doubles.

4. The basic PWM dc drive is said to be unidirectional. Explain why.

The basic PWM dc motor drive is said to be unidirectional because it cannot reverse the polarity of the voltage applied to the dc motor. This is because a buck chopper is used.

5. What is the result of an increase in the friction torque of the mechanical load coupled to a dc motor powered by a basic PWM dc motor drive?

The speed of rotation of the dc motor decreases.

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