

Electricity and New Energy
DC Power Electronics

Courseware Sample

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By the staff of Festo Didactic

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

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Safety and Common Symbols

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

Symbol	Description
	DANGER indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
	WARNING indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
	CAUTION indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
	CAUTION used without the <i>Caution, risk of danger</i> sign  , indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal

Safety and Common Symbols









Symbol	Description
	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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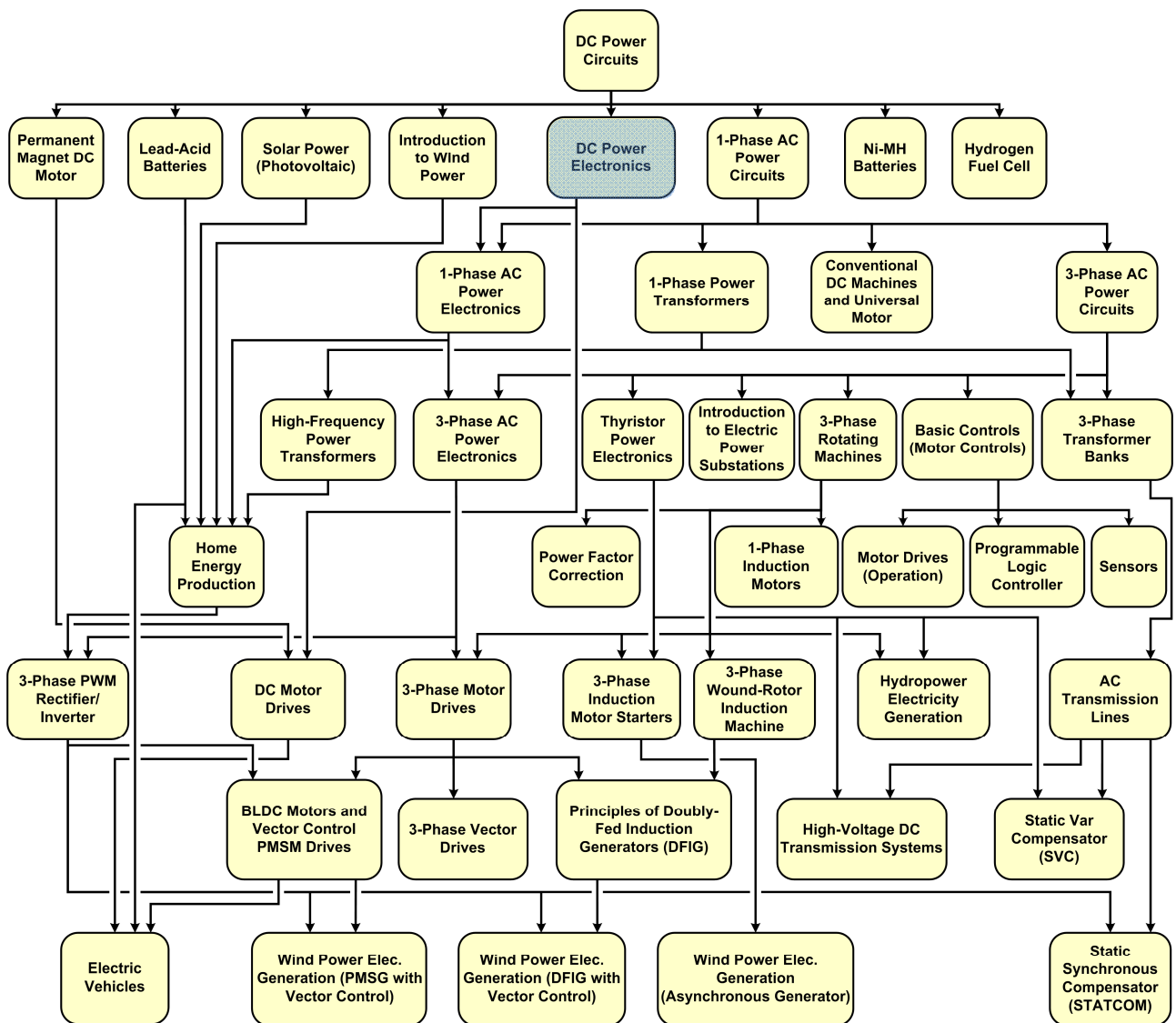
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Preface

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 home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

This course covers power electronic components and circuits (choppers) required to manage dc power, such as dc power stored in batteries or produced from wind power or solar power. The course presents the diode and the switching transistor, two semiconductor components that are widely used in power electronics. The course also provides in-depth coverage of various types of chopper, a power electronics device used in many DC power circuits (e.g., dc motor drives, battery chargers, dc-to-dc converters, etc.).

Manual objectives

When you have completed this manual, you will be familiar with the main types of choppers. You will also be familiar with high-speed power switching (voltage-type and current-type circuits, free-wheeling diodes, etc.). Finally, you will know how to control ripple in choppers, and to build a battery charger using a buck chopper.

Safety considerations

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

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.

Prerequisite

As a prerequisite to this course, you should have read the manual titled *DC Power Circuits*, part number 86350.

Systems of units

Units are expressed using the International System of Units (SI) followed by the 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 manual should be considered as a guide. Students who correctly performed 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, part number 38486-E.

Sample Exercise
Extracted from
the Student Manual
and the Instructor Guide

The Lead-Acid Battery Charger

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the operation of a lead-acid battery charger implemented using a buck chopper with feedback loops.

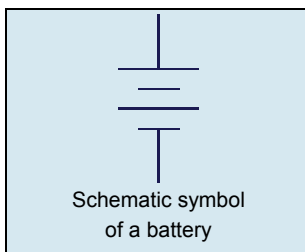
DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Battery fundamentals
- Lead-acid battery charger fundamentals
- Implementing a lead-acid battery charger using a buck chopper with feedback loops

DISCUSSION

Battery fundamentals



A battery is a device that converts chemical energy into electric energy by means of an electrochemical reaction. When a load such as a resistor or a small light bulb, is connected to the terminals of a battery, a chemical reaction starts and electricity is produced and consumed by the load. When no load is connected to the battery terminals, no chemical reaction occurs and no electrical energy is produced.

There are three major types of batteries: primary (single use), secondary (rechargeable), and reserve (for long storage periods). The primary batteries are discarded when discharged. They are commonly used as a power source for portable electronic and electrical devices. The secondary batteries can be electrically recharged. They can be used as an energy-storage device, which is usually electrically connected to and charged by an energy source that delivers energy to a load on demand, as in automotive applications, emergency systems, and stationary energy storage systems. The lead-acid batteries are secondary batteries.

The basic electrochemical unit that produces electric energy is referred to as a **cell**. A battery consists of a series/parallel arrangement of several cells. For example, the 12 V lead-acid battery shown in Figure 40 and used in any internal-combustion engine (ICE) car for starting, lighting, and ignition (SLI battery) consists of six cells connected in series, each cell having a nominal output voltage (voltage under load) of about 2 V. The Lead-Acid Battery Pack of your training system consists of four 12 V batteries connected in series, each battery containing 6 cells.

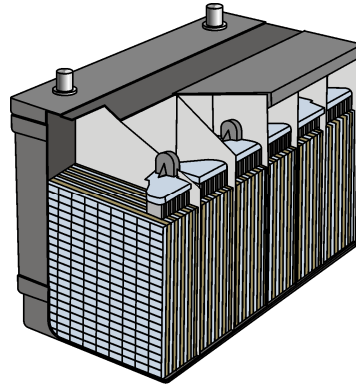


Figure 40. A 12 V lead-acid battery contains six cells.

The **capacity** (C) of a battery is a measure of the amount of energy that can be delivered by a battery when it is fully charged, and it is usually expressed in ampere-hour (Ah). The capacity of a lead-acid battery is usually determined by measuring the average load current during a discharge test that lasts a specific time and brings the battery voltage down to a preset end value at which the battery is considered to be completely discharged. When the capacity is determined using a test that lasts 20 hours, it is designated as the capacity C_{20} . For instance, a lead-acid battery rated for 200 Ah ($10\text{ A} \times 20\text{ h}$) will deliver 10 A of current for 20 hours under standard temperature conditions.

Lead-acid battery charger fundamentals

A lead-acid battery can be recharged by connecting a source of electric power to the battery. The battery charging process uses the electric power supplied by the source to convert the active chemicals in the battery to their original high-energy state.

For the conversion of the active chemicals to their original high-energy state to be safe and cause no harm to the battery, the voltage and current of the dc power source must be carefully controlled during battery charge. In particular, the lead-acid battery should not be allowed to overheat or to produce too much oxygen and hydrogen gas (this is commonly referred to as gassing) due to electrolysis of the water contained in the electrolyte of the battery. When too much gassing occurs, water is lost from the battery electrolyte, thereby reducing the amount of electrolyte and modifying its chemical composition – two harmful consequences leading to a deterioration in performance of any lead-acid battery and a shortened life. Gassing occurs in a lead-acid battery when the charging voltage measured across the battery exceeds a certain value, referred to as the gassing voltage. The gassing voltage is about 57.6 V for a 48 V lead-acid battery pack.

Many methods of charging can be used to charge lead-acid batteries. In this exercise, you will use the “modified constant-voltage charging method” (fast charging method).

In the initial stage of the fast charging method, the battery charge starts with a constant current set to the maximum charging current recommended by the battery manufacturer. The charging current is maintained at this value until a certain voltage is reached, usually the gassing voltage (about 2.4 V/cell). See Figure 41.

When the gassing voltage is reached, battery charging continues with a constant-voltage just equal to or slightly below the gassing voltage until the current flowing through the battery decreases to a rate of one tenth of the battery capacity ($0.1C_{20}$). This stage corresponds to the middle stage of the battery charge as shown in Figure 41. Note that the charging current rate shown in Figure 41 applies to a 48 V lead-acid battery.

In the finishing stage of charge, the voltage is reduced to the float voltage to complete and maintain the battery charge. Float voltage refers to the constant voltage that is applied continuously to a battery to maintain it in a fully charged condition. Typical float voltage is about 55.2 V for a 48 V battery pack.

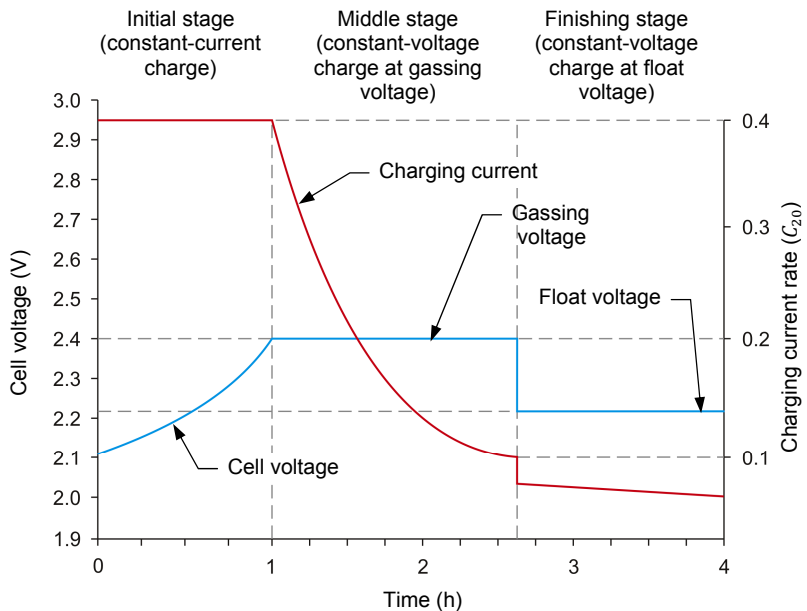


Figure 41. Modified constant-voltage charging method (fast charging method).

Implementing a lead-acid battery charger using a buck chopper with feedback loops

As learned in the previous exercises, the voltage conversion occurring in a buck chopper is controlled by adjusting the duty cycle of the signal controlling the electronic switch in the chopper. The average voltage at the chopper output is a portion of the voltage applied to the chopper input. Thus, when the voltage applied to the chopper input is varied, the chopper output voltage varies. Also, the higher the duty cycle, the closer the average output voltage to the input voltage. Similarly, when the load at the buck chopper output varies, the load current also varies if the buck chopper input voltage and the duty cycle remain constant.

To charge a battery using the fast charging method, the current during the initial stage of battery charge and the voltage during the middle and finishing stages of battery charge must be consistently maintained across the battery, even if the battery characteristics change due to variations in the battery state of charge. To do this, the battery current or voltage must be continuously monitored and the duty cycle of the switching control signal of the switch in the buck chopper readjusted to take into account the load variations due to variations in the battery state of charge. Figure 42 shows a simplified diagram of a battery charger implemented using a buck chopper with the voltage and current feedback loops required. In this battery charger circuit, the battery voltage and current are monitored by voltage sensor E and current sensor I. In brief, each of these sensors transmits a feedback signal to a controller, which sets the duty cycle of the switching control signal in the buck chopper to the value required to maintain the current or the voltage across the battery at the desired value.

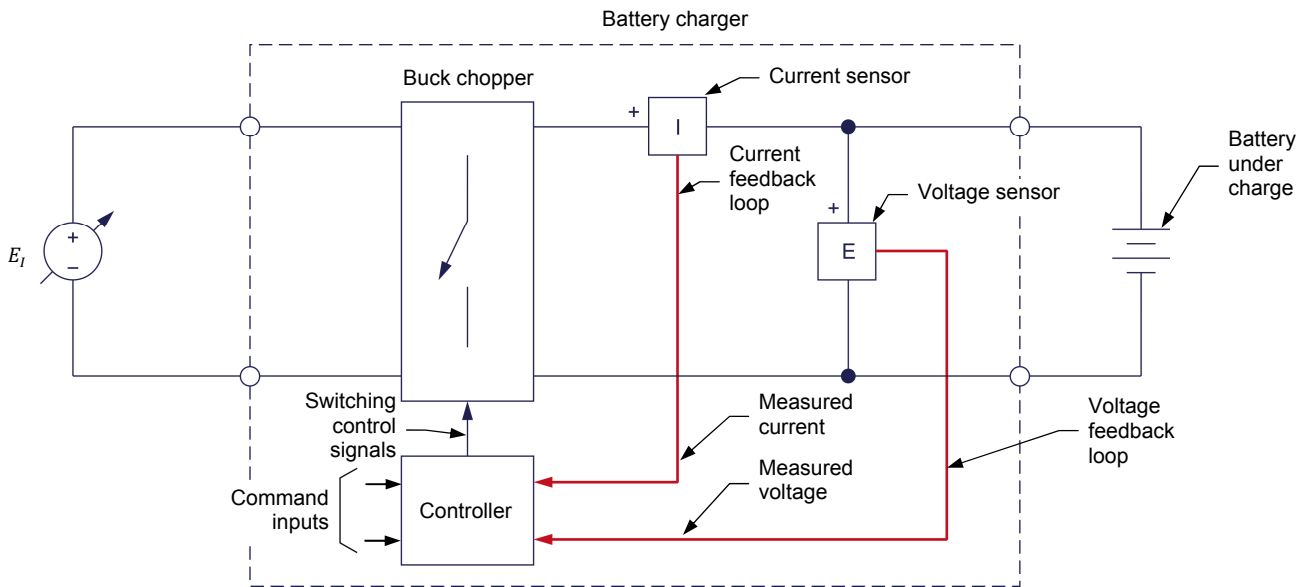


Figure 42. Simplified block diagram of a lead-acid battery charger implemented using a buck chopper with voltage and current feedback loops.

A command signal is a target value that an automatic control system aims to reach.

The voltage and current feedback loops in the battery charger shown above can be implemented using the *Buck Chopper with Feedback* function of *LVDAC-EMS*. Inputs *E4* and *I4* of a *Data Acquisition and Control Interface (DACI)* are used as voltage and current sensors to monitor the battery voltage and current. The voltage and current signals from these sensors are filtered to remove the ripple and noise, and each signal is compared with a command signal in an error detector. The difference (error) between the measured signal value and the command signal is then amplified in a proportional and integral (PI) amplifier and sent to a PWM signal generator to readjust the duty cycle of the buck-chopper switching control signal in order to increase or decrease the buck-chopper output voltage so that the measured voltage or current equals the voltage or current command. The block diagram of this battery charger is shown in Figure 43.

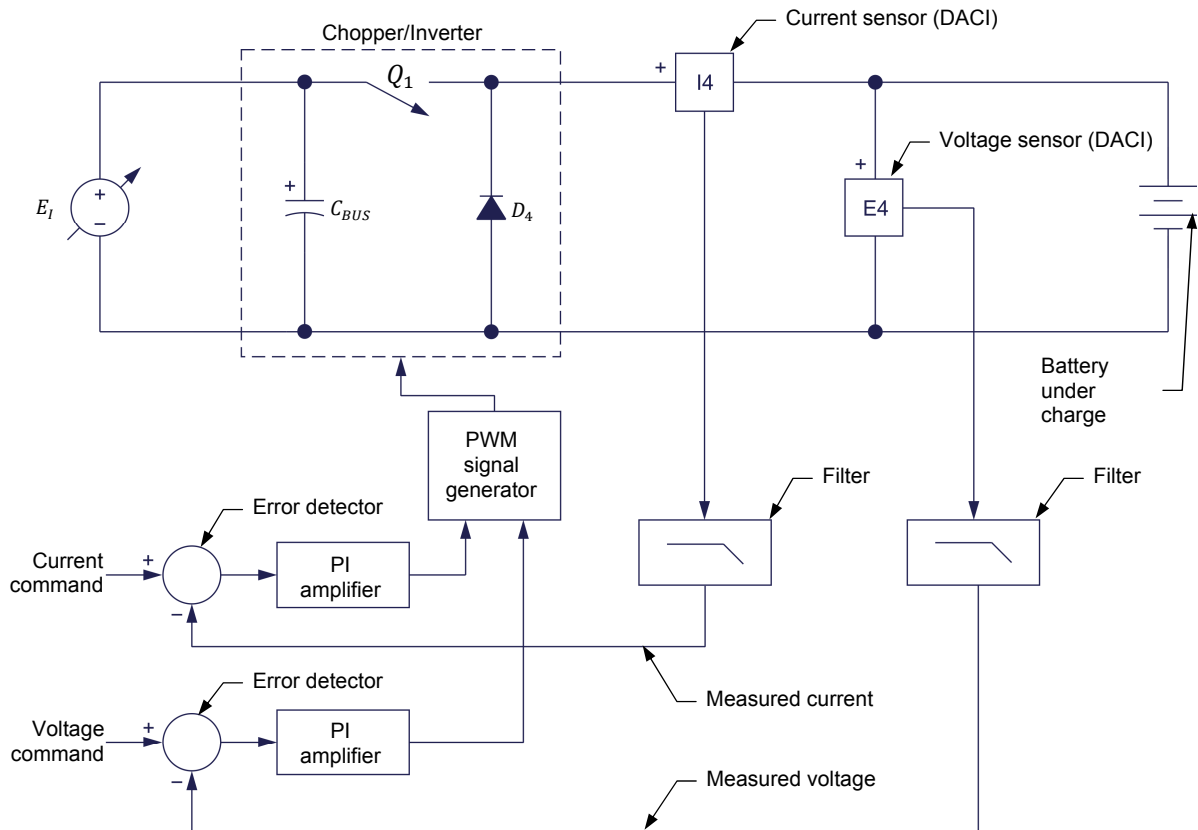


Figure 43. Block diagram of the lead-acid battery charger that can be implemented using the Buck Chopper with Feedback function of LVDAC-EMS, a Data Acquisition and Control Interface (DACI), a Chopper/Inverter module, and a dc power source.

For instance, when the voltage measured across the battery is less than the voltage set by the voltage command, the error detector signal is positive thereby increasing the duty cycle of the buck chopper switching control signal. This causes the voltage across the battery to increase until the error is corrected. At this point, the error detector signal is zero and the PI amplifier produces a fixed signal that sets the duty cycle of the buck chopper switching control signal to the exact value required to maintain equilibrium.

Similarly, when the current flowing through the battery is less than the current set by the current command, the error detector signal is positive thereby increasing the duty cycle of the buck chopper switching control signal. This causes the current flowing through the battery to increase until the error is corrected. At this point, the error detector signal is zero and the PI amplifier produces a fixed signal that sets the duty cycle of the buck chopper switching control signal to the exact value required to maintain equilibrium.

The current loop is used during the first phase of the battery charge and the voltage loop is used during the second and third phases of the battery charge.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Voltage regulation
- Current regulation
- Partially discharging the batteries in the Lead-Acid Battery Pack
- The lead-acid battery charger

PROCEDURE



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

Setup and connections



Before beginning this exercise, measure the open-circuit voltage across the Lead-Acid Battery Pack, Model 8802, using a multimeter. If the open-circuit voltage is lower than 51 V, ask your instructor for assistance as the Lead-Acid Battery Pack is probably not fully charged. Appendix C of this manual indicates how to prepare (charge) the Lead-Acid Battery Pack before each laboratory period.

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 this exercise.

Install the required equipment in the [Workstation](#).

2. Connect the *Power Input* of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply.

Connect the *Low Power Input* of the [IGBT Chopper/Inverter](#) to the *Power Input* of the [Data Acquisition and Control Interface](#). Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) 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.

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

Set the *Operating Mode* switch of the *Four-Quadrant Dynamometer/Power Supply* to *Power Supply*.

Turn the *Four-Quadrant Dynamometer/Power Supply* on by setting the main power switch to *I* (on).

5. Connect the *Digital Outputs* of the *Data Acquisition and Control Interface (DACI)* to the *Switching Control Inputs* of the *IGBT Chopper/Inverter* using a DB9 connector cable.

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

In the *LVDAC-EMS Start-Up* window, make sure that the *Data Acquisition and Control Interface* and the *Four-Quadrant Dynamometer/Power Supply* are detected. Make sure that the *Computer-Based Instrumentation* and *Chopper/Inverter Control* functions for the *Data Acquisition and Control Interface* are available, as well as the *Standard Functions (C.B. control)* for the *Four-Quadrant Dynamometer/Power Supply*. 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.

7. Set up the circuit shown in Figure 44. In this circuit, inputs *E4* and *I4* are used by *LVDAC-EMS* as feedback inputs for the buck chopper. Note that when inputs *E4* and *I4* are used by *LVDAC-EMS* as feedback inputs, they are no longer available for the *LVDAC-EMS* instrumentation, i.e., the *Metering*, *Oscilloscope*, *Phasor Analyzer*, and *Harmonic Analyzer*. Other voltage and current inputs of the DACI must be used to measure and observe the voltage and current sensed by inputs *E4* and *I4*.

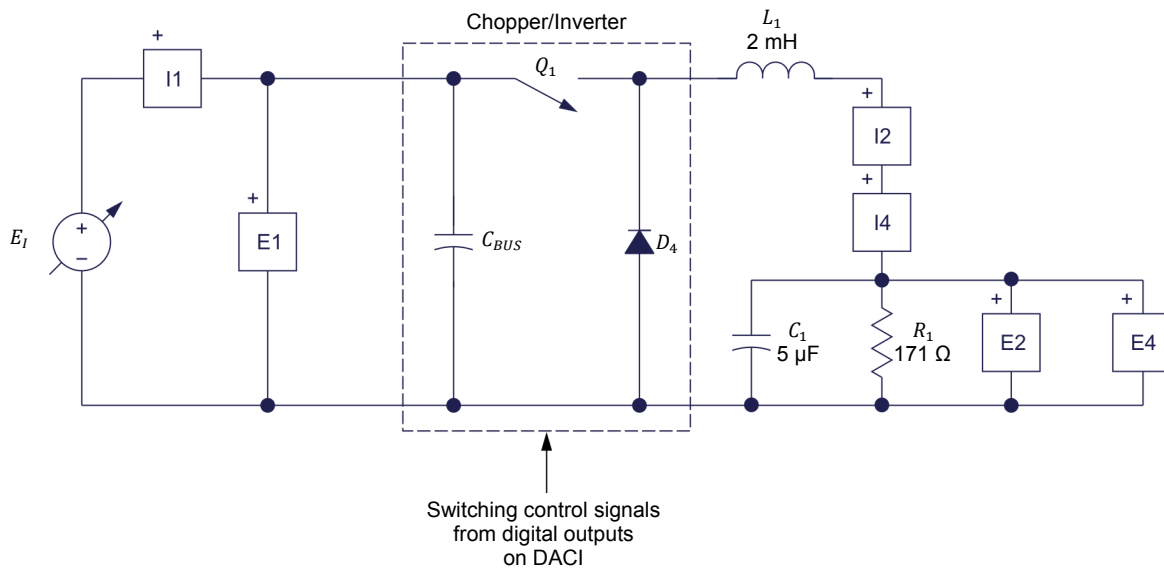


Figure 44. Circuit used to observe voltage and current regulation.

8. Make the necessary connections and switch settings on the **Resistive Load** in order to obtain the resistance value required.

Voltage regulation

In this part of the exercise, you will apply a voltage across a resistor connected to the output of a buck chopper with feedback, and observe that the voltage is maintained by the voltage regulation circuit although the input voltage of the chopper is changed.

9. In the **Data Acquisition and Control Settings** of LVDAC-EMS, set the range of **E4** to **Low**. This corresponds to a 0 V to 80 V range.
10. In LVDAC-EMS, open the **Four-Quadrant Dynamometer/Power Supply** window and make the following settings:
 - Select the **Voltage Source (+)** function.
 - Set the voltage to 60 V.
 - Do not start the voltage source now.

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

- Select the *Buck Chopper with Feedback* function.
- Set the switching frequency 20 000 Hz.
- Set the *Command Input* parameter to *Knob*.
- Set the *Command* parameter to 100%. This parameter is used to set the command (i.e., the value at which the voltage will be regulated). The *Command* parameter is expressed as a percentage of the *Feedback Range* parameter.
- Set the *Controller Proportional Gain Kp* parameter to 1.0.
- Set the *Controller Integral Gain Ki* parameter to 20.
- Set the *Feedback Input* parameter to *E4*. This sets input *E4* as the feedback input (sensor). This selection allows regulation of the voltage measured using input *E4* (i.e., the buck chopper output voltage).
- Set the *Feedback Range* parameter to 50 V. This parameter determines the value at the selected feedback input that corresponds to a command value of 100%. In the present case, this makes a voltage of 50 V measured at input *E4* correspond to a command value of 100%, so that the regulated voltage will be 50 V (100% × 50 V).
- Set the *Feedback Filter Cutoff Frequency* to 100 Hz. This sets the cutoff frequency of the feedback filter to 100 Hz.
- Make sure that the *Acceleration Time* is set to 0.0 s.
- Make sure that the *Deceleration Time* is set to 0.0 s.
- Make sure that the Q_1 parameter is set to *PWM*.
- Start the buck chopper with feedback.

12. From the parameters set in the **Chopper/Inverter Control** window, predict the voltage across resistor R_1 .

Voltage across resistor R_1 : _____

Voltage across resistor R_1 : 50 V (100% of the feedback range value, which is 50 V).

13. What effect will a voltage variation at the buck chopper input have on the voltage across resistor R_1 ? Explain.

As long as the voltage at the buck chopper input remains higher than 50 V, the voltage across resistor R_1 will not be affected by a voltage variation. The voltage across resistor R_1 will be maintained by the regulation circuit, which will adjust the duty cycle as required.

14. What will the duty cycle set by the regulation circuit be if the chopper input voltage is successively set to 80 V, 100 V, and 120 V?

Duty cycle when the input voltage is 80 V: _____

Duty cycle when the input voltage is 100 V: _____

Duty cycle when the input voltage is 120 V: _____

Duty cycle when the input voltage is 80 V: 63%

Duty cycle when the input voltage is 100 V: 50%

Duty cycle when the input voltage is 120 V: 42%

15. In LVDAC-EMS, open the **Metering** window. Make sure that meters $E1$, $E2$, $I1$, and $I2$ are enabled. Select the **DC** mode by setting the **AC/DC** button at the bottom of each meter to **DC**. Disable meter $E4$.

Select the **Continuous Refresh** mode by clicking on the **Continuous Refresh** button.

16. Start the voltage source.

17. Successively set the chopper input voltage (meter $E1$ in the **Metering** window) to each of the values shown in Table 8. For each value, record the duty cycle (indicated by meter $D1$ in the **Chopper/Inverter Control** window) as well as the voltage across resistor R_1 (meter $E2$ in the **Metering** window).

Table 8. Duty cycle and voltage across resistor R_1 .

Input voltage (V)	Duty cycle (%)	Voltage across resistor R_1 (V)
80		
100		
120		

Table 8. Duty cycle and voltage across resistor R_1 .

Input voltage (V)	Duty cycle (%)	Voltage across resistor R_1 (V)
80	63	50
100	50	50
120	42	50

18. Do your measurements confirm the predictions you made in step 14?

Yes No

Yes

19. What will the duty cycle and the voltage across resistor R_1 be if the input voltage were set to a value lower than the expected regulated voltage such as 40 V?

Duty cycle: _____

Voltage across resistor R_1 : _____

Duty cycle: 100%

Voltage across resistor R_1 : approximately 40 V

20. In the **Four-Quadrant Dynamometer/Power Supply** window, set the source voltage to 40 V and validate your predictions made in the previous step. Are your predictions confirmed?

Yes No

Yes

21. Stop the buck chopper and the voltage source.

Current regulation

In this part of the exercise, you will make a current flow through a resistor connected to the output of a buck chopper with feedback, and observe that the current is maintained by the current regulation circuit although the resistor value is changed. You will also observe that the current remains constant even when the voltage at the buck chopper input is changed.

- 22.** In the **Data Acquisition and Control Settings** window of LVDAC-EMS, make sure that the range of input **E4** is set to **Low**.

Make sure that the range of input **I4** is set to **Low**. This corresponds to a range of 0 A to 4 A.

- 23.** Make sure that the connections and the switches on the **Resistive Load** are set to obtain 171 Ω as the resistance value for R_1 .

- 24.** In the **Four-Quadrant Dynamometer/Power Supply** window, make the following setting:

- Set the source voltage to 100 V.

- 25.** In the **Chopper/Inverter Control** window, make the following settings:

- Make sure that the **Buck Chopper with Feedback** function is selected.
- Make sure that the **Switching Frequency** is set to 20 000 Hz.
- Make sure that the **Command Input** parameter is set to **Knob**.
- Make sure that the **Command** parameter is set to 100%. This sets the regulated output current to 100% of the **Feedback Range** parameter value.
- Make sure that the **Controller Proportional Gain K_p** parameter is set to 1.0
- Make sure that the **Controller Integral Gain K_i** parameter is set to 20.
- Set the **Feedback Input** parameter to **I4**. This sets input **I4** as the feedback input (sensor). This selection allows regulation of the current measured using input **I4** (i.e., the buck chopper output current).
- Set the **Feedback Range** parameter to 0.5 A. This makes a current of 0.5 A measured using input **I4** correspond to a command value of 100%.
- Make sure that the **Feedback Filter Cutoff Frequency** is set to 100 Hz.

- Make sure that the *Acceleration Time* is set to 0.0 s.
- Make sure that the *Deceleration Time* is set to 0.0 s.
- Make sure that the Q_1 parameter is set to *PWM*.
- Start the buck chopper with feedback.

26. From the parameters set in the *Chopper/Inverter Control* window, what will the current flowing through resistor R_1 be?

Current flowing through resistor R_1 : _____

Current flowing through resistor R_1 : 0.5 A (100% of 0.5 A)

27. What effect will reducing the value of resistor R_1 have on the current flowing through resistor R_1 ? Explain.

The current flowing through resistor R_1 will not vary. It will be maintained by the regulation circuit, which will adjust the duty cycle of the buck chopper as required.

28. What effect will increasing the voltage at the buck chopper input have on the current flowing through resistor R_1 ? Explain.

The current flowing through resistor R_1 will not vary. It will be maintained by the regulation circuit, which will adjust the duty cycle of the buck chopper as required.

29. In the *Metering* window of *LVDAC-EMS*, make sure that meters *E1*, *E2*, *I1*, and *I2* are enabled, and that the *DC* mode is selected on each meter. Make sure that meter *I4* is disabled.

Make sure that the *Continuous Refresh* mode is selected.

30. Start the voltage source.

Successively set the resistance of resistor R_1 to each of the values shown in Table 9. For each value, record the duty cycle (meter $D1$ in the **Chopper/Inverter Control** window) as well as the current flowing through resistor R_1 (meter $I2$ in the **Metering** window).

Table 9. Duty cycle and current flowing through resistor R_1 .

Resistance (Ω)	Duty cycle (%)	Current flowing through resistor R_1 (A)
171		
86		
57		

Table 9. Duty cycle and current flowing through resistor R_1 .

Resistance (Ω)	Duty cycle (%)	Current flowing through resistor R_1 (A)
171	89.2	0.50
86	44.5	0.50
57	30.1	0.50

31. Do your measurements confirm your predictions made in step 26 and step 27?

Yes No

Yes

32. Increase the source voltage to 140 V. Record the duty cycle (meter $D1$ in the **Chopper/Inverter Control** window) as well as the current flowing through resistor R_1 (meter $I2$ in the **Metering** window).

Duty cycle: _____

Current flowing through resistor R_1 : _____

Duty cycle: 25.5%

Current flowing through resistor R_1 : approximately 0.5 A

33. Do your measurements confirm your predictions made in step 28?

Yes No

Yes

34. What will the current flowing through resistor R_1 be if the *Command* parameter is set to 80%?

Current flowing through resistor R_1 : _____

Current flowing through resistor R_1 : 0.4 A (80% of the feedback range value, which is 0.5 A).

35. In the *Chopper/Inverter Control* window, set the *Command* parameter to 80% and validate your prediction made in the previous step. Is your prediction confirmed?

Yes No

Yes

36. Stop the buck chopper and the voltage source.

Partially discharging the batteries in the Lead-Acid Battery Pack

In this part of the exercise, you will partially discharge the batteries in the Lead-Acid Battery Pack to obtain the operating conditions required in the next part of the exercise.

37. Disconnect the *Four-Quadrant Dynamometer/Power Supply* from the current circuit by disconnecting the leads at the yellow and white terminals. The rest of the circuit will be used later in the exercise.

Connect the positive (red) terminal of the *Lead-Acid Battery Pack* to the *Power Supply* yellow terminal of the *Four-Quadrant Dynamometer/Power Supply*. Connect the negative (black) terminal of the *Lead-Acid Battery Pack* to the *Power Supply* white terminal of the *Four-Quadrant Dynamometer/Power Supply*.

38. In the **Four-Quadrant Dynamometer/Power Supply** window of LVDAC-EMS, make the following settings:
- Set the *Function* parameter to *Battery Discharger (Constant-Current Timed Discharge with Voltage Cutoff)*. When this function is selected, the **Four-Quadrant Dynamometer/Power Supply** operates as a negative current source whose operation is controlled by parameters associated with battery discharge.
 - Set the *Discharge Current* parameter to 4 A. This sets the discharge current of the battery discharger to 4 A.
 - Set the *Discharge Duration* parameter to 20 min. This sets the discharge duration to 30 minutes.
 - Set the *Cutoff Voltage* parameter to 40 V. This sets the minimum value (40 V) to which the battery voltage is allowed to decrease during discharge. This limits battery discharging to prevent damage to the batteries.
 - Start the Battery Discharger by setting the *Status* parameter to *Started* or by clicking on the *Start/Stop* button.



During battery discharging, the time left is indicated at the bottom of the **Four-Quadrant Dynamometer/Power Supply** window. Once battery discharge is completed, the Battery Discharger automatically stops and the *Status* parameter is set to *Stopped*.

Once battery discharge is completed, disconnect the *Power Supply* terminals of the **Four-Quadrant Dynamometer/Power Supply** from the **Lead-Acid Battery Pack** and proceed with the next part of the exercise.



Make sure that the Battery Discharger is stopped (i.e., make sure that the *Status* parameter is set to *Stopped*) before proceeding with the next part of the exercise.

The lead-acid battery charger

In this part of the exercise, you will perform the initial stage and the middle stage of the modified constant-voltage charging method (fast charging method) for lead-acid batteries, which are illustrated in Figure 41.

Initial stage of a lead-acid battery fast-charging – Constant current charge

In the initial stage of the battery charge, you will make the maximum recommended charge current flow through the **Lead-Acid Battery Pack**, and maintain this current using automatic regulation until the voltage measured across the terminals of the **Lead-Acid Battery Pack** reaches the gassing voltage (57.6 V).

39. Set up the circuit shown in Figure 45. In this circuit, the voltage and current supplied to the **Lead-Acid Battery Pack** are measured using inputs *E2* and *I2*. Inputs *E4* and *I4* are used by LVDAC-EMS as feedback inputs for regulation purposes.

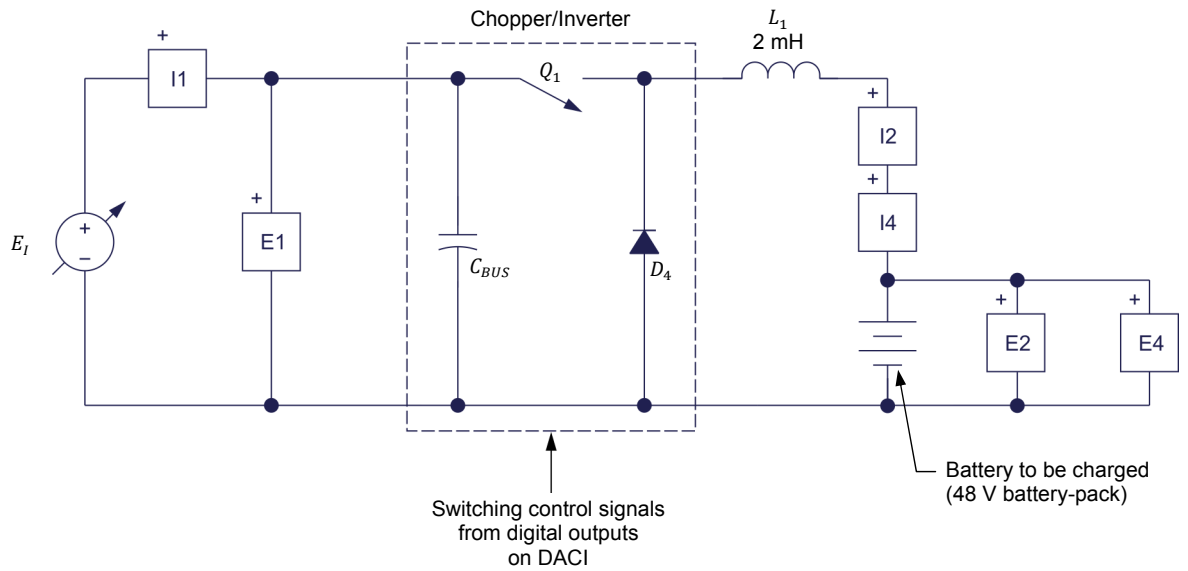


Figure 45. Circuit used to charge the Lead-Acid Battery Pack.

40. In the **Data Acquisition and Control Settings** window of LVDAC-EMS, set the range of the inputs as follows: input E_1 to *High* (0 V to 800 V), inputs E_2 and E_4 to *Low* (0 V to 80 V), inputs I_1 , I_2 and I_4 to *Low* (0 A to 4 A).
41. In the **Four-Quadrant Dynamometer/Power Supply** window, make the following settings:
 - Select the *Voltage Source (+)* function.
 - Set the source voltage to 100 V.
 - Do not start the voltage source now.

42. In the **Chopper/Inverter Control** window, make the following settings:

- Make sure that the *Buck Chopper with Feedback* function is selected.
- Make sure that the *Switching Frequency* parameter is set to 20 000 Hz.
- Make sure that the *Command Input* parameter is set to *Knob*.
- Make sure that the *Command* parameter is set to 100%. This sets the regulated output current to 100% of the *Feedback Range* parameter value.
- Set the *Controller Proportional Gain Kp* parameter to 1.0.
- Set the *Controller Integral Gain Ki* parameter to 20.0.
- Set the *Feedback Input* parameter is set to *I4*. This sets input *I4* as the feedback input. This selection allows regulation of the current measured using input *I4* (i.e., the battery charging current).
- Set the *Feedback Range* parameter to the maximum charge current value of the *Lead-Acid Battery Pack*. When this current is measured at input *I4*, it corresponds to a command value of 100%.
- Make sure that the *Feedback Filter Cutoff Frequency* is set to 100 Hz.
- Make sure that the *Acceleration Time* is set to 0.0 s.
- Make sure that the *Deceleration Time* is set to 0.0 s.
- Make sure that the Q_1 parameter is set to *PWM*.
- Start the buck chopper.

43. In the **Metering** window, make the following settings:

- Make sure that meters *E1*, *E2*, *I1*, and *I2* are enabled, and the *DC* mode is selected on each meter.
- Make sure that meters *E4* and *I4* are disabled.
- Make sure that the *Continuous Refresh* mode is selected.

44. Start the voltage source and immediately record the duty cycle displayed by the *Duty Cycle* meter in the **Chopper/Inverter Control** window.

Duty cycle: _____

Duty cycle: approximately 57% (the current duty cycle depends on the state of charge of the Lead-Acid Battery Pack).

45. Record the voltage across the Lead-Acid Battery Pack (meter *E2* in the Metering window).

Voltage across the Lead-Acid Battery Pack: _____

Voltage across the Lead-Acid Battery Pack: approximately 54 V

46. Record the current flowing through the Lead-Acid Battery Pack (meter *I2* in the Metering window).

Current flowing through the Lead-Acid Battery Pack: _____

Current flowing through the Lead-Acid Battery Pack: 2.8 A

47. Does the current flowing through the Lead-Acid Battery Pack correspond to the parameters set in the Chopper/Inverter Control window?

Yes No

Yes

48. Observe the voltage across the Lead-Acid Battery Pack displayed by meter *E2*. The voltage should slowly increase. Once the voltage has reached the gassing voltage (57.6 V), record the duty cycle displayed by the *Duty Cycle* meter in the Chopper/Inverter Control window, and **immediately stop** the buck chopper with feedback. Permanent damage to the batteries in the Lead-Acid Battery Pack may occur if the voltage exceeds the gassing voltage significantly.



The duty cycle value displayed is slightly higher than the theoretical value, due to voltage drops across transistor Q_1 of the Chopper/Inverter and inductor L_1 .

Duty cycle: _____

Duty cycle: 61%

49. Compare the duty cycle measured at the beginning of the initial stage of battery charge (step 44) with the duty cycle measured at the end of the initial stage (step 48).

You should observe that the duty cycle has increased slightly to maintain the charge current constant despite the increase in the battery-pack voltage.

Middle stage of a lead-acid battery fast-charging – Constant voltage charge at gassing voltage

In the middle stage of the battery charge, you will apply a voltage of 57 V (a little below the gassing voltage) across the Lead-Acid Battery Pack and maintain this voltage constant using automatic regulation until the current flowing through the battery pack has decreased to a value corresponding to $0.1C_{20}$.

- 50.** Do not modify the settings in the [Data Acquisition and Control Settings, Four-Quadrant Dynamometer/Power Supply](#) window, and [Metering](#) window.

Make the following settings in the [Chopper/Inverter Control](#) window:

- Set the [Feedback Input](#) parameter to [E4](#). This sets input [E4](#) as the feedback input, and allows regulation of the voltage measured using input [E4](#) (i.e., the battery charging voltage).
- Set the [Feedback Range](#) parameter to 57.0 V. This makes a voltage of 57.0 V measured at input [E4](#) correspond to a command value of 100%.
- Do not modify the settings of the other parameters in the [Chopper/Inverter Control](#) window.
- Do not start the buck chopper with feedback for now.

- 51.** From the settings made in [LVDAC-EMS](#), determine the duty cycle which the regulation circuit will use at the beginning of the middle stage of the battery charge.

Duty cycle at the beginning of the middle stage of battery charge: _____

Duty cycle at the beginning of the middle stage of battery charge: approximately 57.6%

- 52.** Start the buck chopper with feedback. Wait for the duty cycle displayed by the [Duty Cycle](#) meter in the [Chopper/Inverter Control](#) window to stabilize, then record the value.

Duty cycle: _____

Duty cycle: 61%

- 53.** Does the measured duty cycle confirm your prediction in step 51?

Yes No

Yes

54. Record the voltage across the **Lead-Acid Battery Pack** (meter E_2 in the **Metering** window).

Voltage across the **Lead-Acid Battery Pack**: _____

Voltage across the **Lead-Acid Battery Pack**: 57.6 V

55. Wait about 10 minutes for the battery charge to progress.

In the **Four-Quadrant Dynamometer/Power Supply** window, decrease the voltage E_1 to 80 V.

Does the voltage measured across the **Lead-Acid Battery Pack** decrease when the voltage E_1 is decreased? Explain why.

No. The voltage measured across the **Lead-Acid Battery Pack** is maintained by the voltage regulation loop of the buck chopper with feedback.

56. Observe the current flowing through the **Lead-Acid Battery Pack** displayed by meter I_2 . The current should decrease slowly. Once the current flowing through the battery pack has decreased to a value corresponding to a value of $0.1C_{20}$, stop the voltage source and the buck chopper with feedback. This completes the middle stage of the battery charge.

Finishing stage of a lead-acid battery fast-charging – Constant voltage charge at float level

At this point, most of the energy supplied by the Lead-Acid Battery Pack during the discharge has been returned to the battery pack. To complete and maintain the battery charge, the voltage applied to the battery pack should be reduced to the float voltage value (52.2 V) and maintained at this value indefinitely. During the finishing stage, the current flowing through the battery pack decreases to a very low value. You do not have to perform this stage of battery charging.

57. Close **LVDAC-EMS**, turn off all equipment, and remove all leads and cables.

CONCLUSION

In this exercise, you were introduced to lead-acid batteries and learned how to charge a lead-acid battery using the modified constant-voltage charging method (also called fast charging method). You were also introduced to the buck chopper with feedback, an automatic regulation system which uses a voltage or current sensor to return a feedback signal to a controller in order to maintain the voltage or current equal to the command value. You implemented a lead-acid battery charger using a buck chopper with feedback and charged a 48 V lead-acid battery pack using the fast charging method.

REVIEW QUESTIONS

1. What is the basic electrochemical unit that produces electric energy in a battery (fast charging method)?

The cell.

2. Briefly describe the three stages of the modified constant-voltage charging method (fast charging method).

In the initial stage of the modified constant-voltage charging method, battery charging starts with a constant current set to the maximum charging current recommended by the battery manufacturer. The current is maintained at this value until a certain voltage is reached, usually the gassing voltage. In the middle stage, battery charging continues with a constant-voltage just equal to or slightly below the gassing voltage until the current flowing through the battery, decreases to a rate of one tenth of the battery capacity ($0.1C_{20}$). In the finishing stage of charge, the battery voltage is reduced to the float voltage to complete and maintain the battery charge.

3. Explain how the voltage at the output of a buck chopper can be maintained to a fixed value despite changes in the load current or the input voltage.

The voltage at the output of a buck chopper is continuously monitored by a sensor. The sensor transmits a feedback signal to a controller, which automatically sets the duty cycle of the switching control signal to the value required to maintain the buck chopper output voltage constant.

4. How does the duty cycle of the switching control signal vary when the voltage at the input of a buck chopper with feedback is doubled?

The duty cycle halves.

5. Briefly describe the gassing voltage and the float voltage.

The gassing voltage corresponds to the voltage at which the lead-acid battery starts to produce gases due to electrolysis of the water contained in the electrolyte of the battery. The float voltage corresponds to the constant voltage that is applied to a battery to maintain it in a fully charged condition.

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