Electricity and New Energy

Lead-Acid Batteries

Courseware Sample

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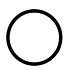
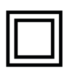
Safety and Common Symbols

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

Symbol	Description
⚠ DANGER	**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 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
3∼	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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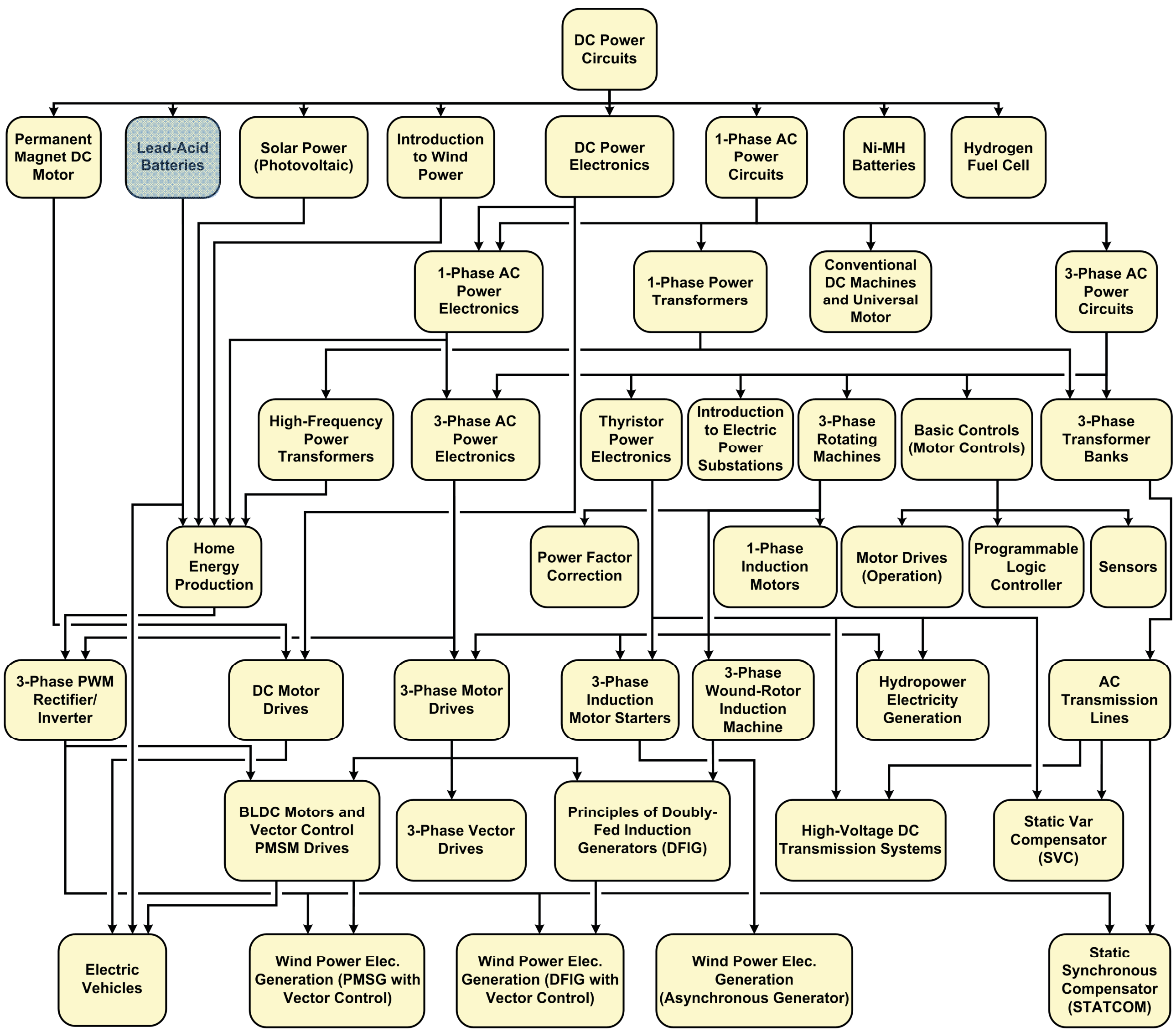
Preface

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

Batteries store electricity in a chemical form, inside a closed-energy system. Some batteries can be re-charged and re-used as a power source in small appliances, machinery, and remote locations. Advances in battery technolog may one day help to solve our energy crisis.

About the course Lead Acid Batteries

The *Lead-Acid Batteries* course is designed to introduce students to the operation of lead-acid batteries. At the beginning of the couse, students are introduced to the voltage regulation, internal resistance, capacity, depth of discharge, and cycle life of lead-acid batteries. Students then learn about and experiment with both the discharge characteristics and the most popular charging methods of lead-acid batteries.

The equipment for the course consists of the Lead-Acid Batteries module and the Four-Quadrant Dynamometer/Power Supply. The Four-Quadrant Dynamometer/ Power Supply is a multifunctional module that is used in the Lead-Acid Batteries course to charge and discharge the batteries. Its operation is controlled by the LVDAC-EMS software, which also provides the instrumentation required to measure, collect, and record the experimental data.

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*, p.n. 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

Battery Charging Methods

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with some methods of charging.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Methods of charging
- Constant-current charging method
- Constant-voltage charging method
- Modified constant-voltage charging method
- Float charging method
- Trickle charging method

DISCUSSION

Methods of charging

A number of methods for charging lead-acid batteries have been developed to meet the "rules for proper charging" presented in the previous exercise. Some of these methods are known as the constant-current method, constant-voltage method, modified constant-voltage method, float charging method, and trickle charging method.

Constant-current charging method

In the constant-current method, a fixed current is applied for a certain time to the battery to recharge it. The charging current is set to a low value (usually less than $0.1C$) to avoid the voltage across the battery from exceeding the gassing voltage as the battery charge approaches 100%. Consequently, this results in long charge times (usually 12 hours or longer). Figure 25a shows the charging characteristic curves obtained with the constant-current method (single step). Multiple decreasing current steps can also be used to shorten charge times obtained using the constant-current charging method as shown in Figure 25b. Though it is used for charging some small lead-acid batteries, the constant-current charging method is not widely used for lead-acid batteries, because of the gassing which is likely to occur when charging a battery too long. The risk of gassing is more important when charging a battery which is only partially-discharged. Constant-current is also used in trickle charging, another charging method described later in this discussion.

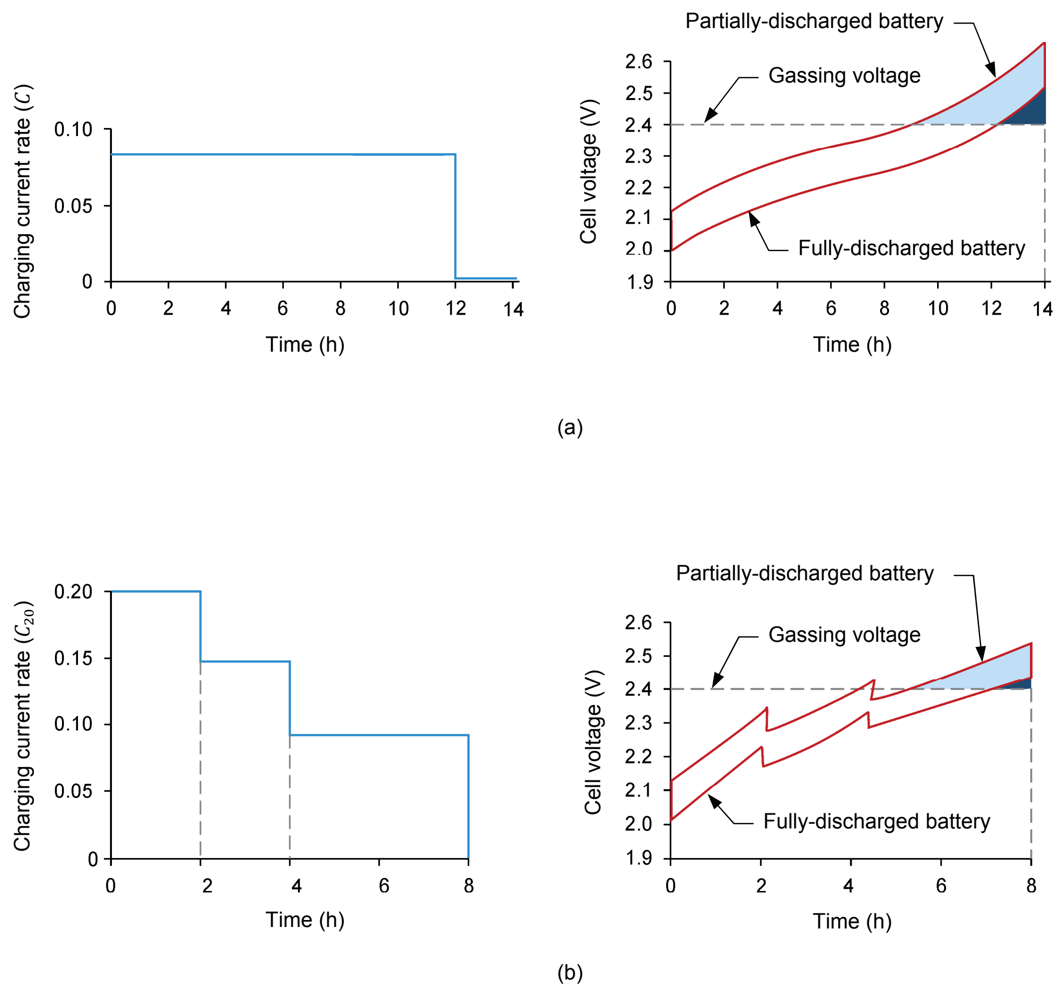


Figure 25. Single-step and multiple-step constant-current charging method.

Constant-voltage charging method

In the constant-voltage charging method, a fixed-voltage is applied to the battery to recharge it. The initial charging current (current at the beginning of the battery charge) is at its maximum and can even reach higher values (even exceeding the maximum charge current prescribed by the battery manufacturer) when the battery depth of discharge is high. For this reason, purely constant-voltage charging is seldom used to charge lead-acid batteries that are used in cyclic charge-discharge applications (e.g., battery in an electric vehicle). However, constant-voltage charging is often used to maintain the charge of lead-acid batteries used in standby applications (e.g., as in uninterruptable power supplies), in which case the charge process is referred to as float charging (another charging method described later in this discussion). Figure 26 shows the charging characteristic curves obtained with the constant-voltage charging method. The waveform difference between the charger output voltage and the battery cell voltage at the beginning of the charge cycle is caused by the internal resistance of the battery.

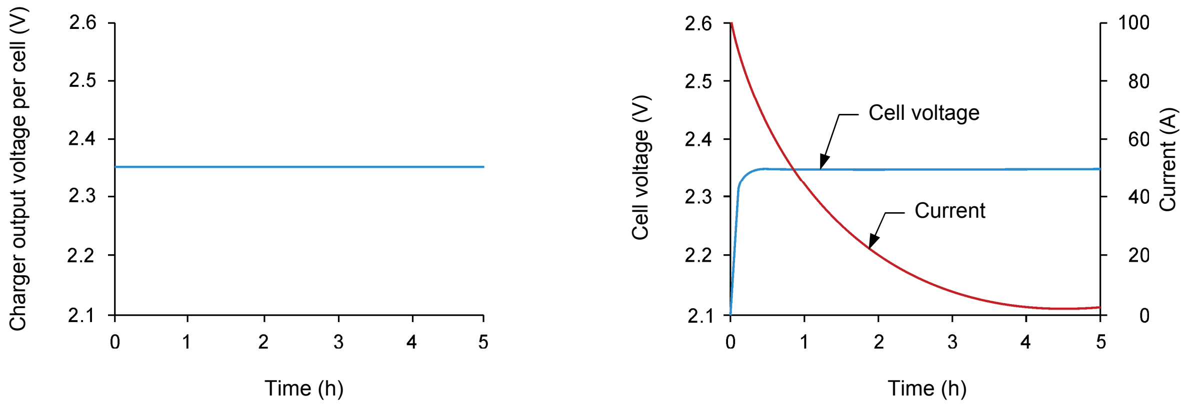


Figure 26. Typical charging characteristics of a SLI battery using the constant-voltage charging method.

Modified constant-voltage charging method

In the modified constant-voltage charging method, both a constant initial current and a constant finishing charge rate (float charging) are used. Battery charging starts with a constant current until a certain voltage is reached (usually the gassing voltage). Battery charging continues with a constant-voltage just equal to or slightly below the gassing voltage until the current decreases to a value of about $0.1C_{20}$. At this point, the constant-voltage is reduced to the float value (see float charging method) to complete and maintain the battery charge. The higher the initial constant-current and constant-voltage, the shorter the charge time. Figure 27 shows the charging characteristic curves obtained with the modified constant-voltage charging method. This charging method is also known as the fast charging method. This charging method is used in the lead-acid battery charger (fast) implemented with the Four-Quadrant Dynamometer/Power Supply.

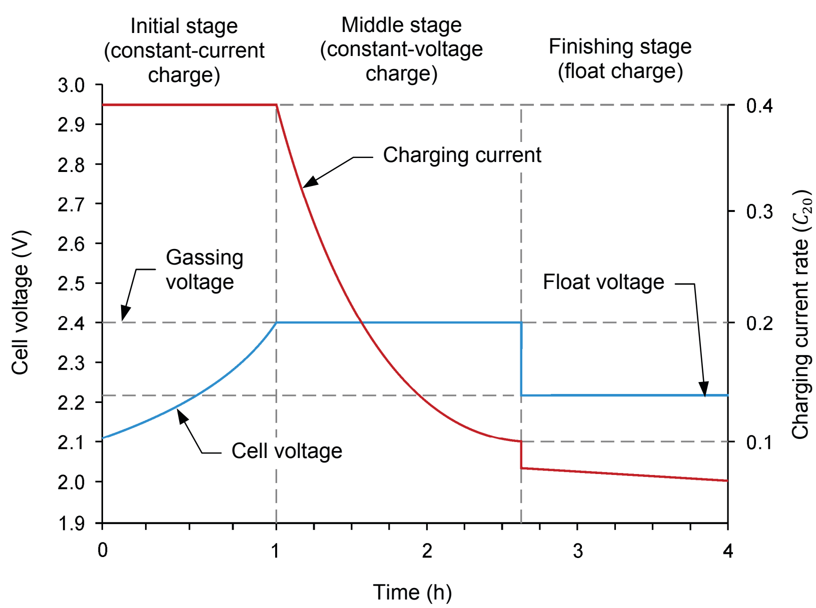


Figure 27. Modified constant-voltage charging method.

Float charging method

In the float charging method, a constant voltage, set to a value just sufficient to finish the battery charge or to maintain the full charge is applied to the battery. Typical float charging voltage values range from about 2.15 V to 2.3 V per battery cell. The float charging method is commonly used to maintain the charge of lead-acid batteries used in stationary applications, such as in uninterruptable power supplies and SLI batteries (when the battery is charged from the motor alternator). Note that to achieve a full recharge with a low constant voltage requires the proper selection of the starting current, which is based on the manufacturer's specifications.

Trickle charging method

In the trickle charging method, a low-value constant current (about $0.01C$) is applied to the battery. This small current is sufficient to maintain the full charge of a battery or to restore the charge of a battery that is used intermittently for short periods of time. The trickle charging method, also called the compensating charge, is used to maintain the charge of batteries used for stationary applications and SLI batteries. During trickle charging, the battery is disconnected from the load (e.g. in the case of an SLI battery, the battery is disconnected from the electrical circuit of the car).

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Battery charge using the modified constant-voltage charging method (fast charge)
- Battery charge using the float charging method (slow charge)

PROCEDURE

Setup and connections

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

Before beginning this exercise, make sure that both batteries in the Lead-Acid Batteries are fully-charged by performing the "Battery state-of-charge (residual capacity) evaluation" described in the Procedure of Exercise 1. If the batteries are not fully charged, ask your instructor for assistance. Appendix B of the Student Manual indicates how to prepare (fully charge) each battery in a Lead-Acid Batteries before each laboratory period.

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

   Install the equipment required in the Workstation.

2. Set the main power switch of the Four-Quadrant Dynamometer/Power Supply 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*.

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

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

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

In the LVDAC-EMS Start-Up window, make sure the Four-Quadrant Dynamometer/Power Supply is detected. Select the network voltage and frequency that correspond to the voltage and frequency of the local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

4. Connect one battery in the Lead-Acid Batteries module to the Four-Quadrant Dynamometer/Power Supply as shown in Figure 28.

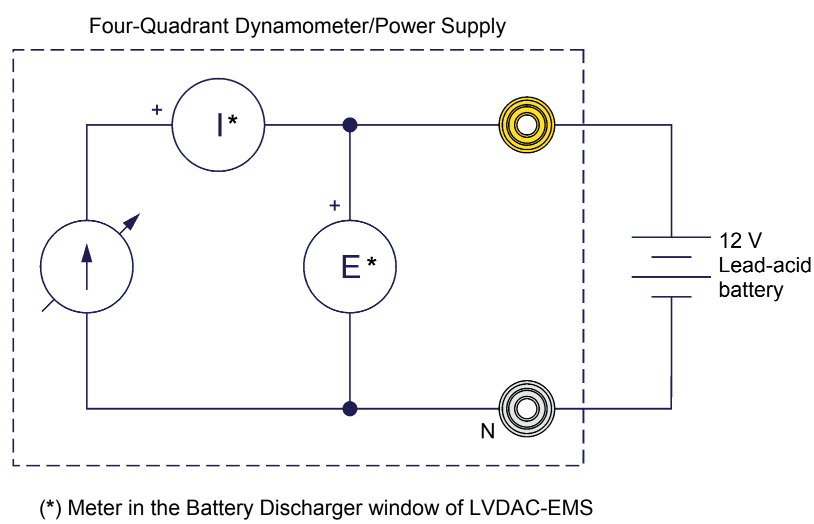


Figure 28. Battery connected to the Four-Quadrant Dynamometer/Power Supply operating as a battery discharger.

Battery charge using the modified constant-voltage charging method (fast charge)

In this part of the exercise, you will first discharge one battery of the Lead-Acid Batteries module to approximately 20% or residual capacity. Then you will charge the battery using the modified constant-voltage charging (fast charge) method. During this charge cycle, you will observe the battery voltage and current as well as the energy returned to the battery.

5. Make sure that both batteries in the Lead-Acid Batteries module are fully-charged by referring to the "Battery state-of-charge (residual capacity) evaluation" section of the Procedure of Exercise 1. If you do not perform the optional float charge in the next part of the exercise, you will need only one battery.

Battery discharge

6. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window and make the following settings:

- Set the *Function* parameter to *Battery Discharger (Constant-Current Timed Discharge with Voltage Cutoff)*.
- Set the *Discharge Current* to 2.3 A (C_{20}).
- Set the *Discharge Duration* to 30 min.
- Set the *Cutoff Voltage* to 9.45 V.
- Reset the meter *Energy*.

The setting of the discharge duration corresponds to the time required to remove approximately 80% of the energy contained in a fully-charged battery when discharging at a rate of C_{20}.

7. In LVDAC-EMS, open the Data Table window. In the *Timer Settings* window of the *Options* menu, set the timer to make 400 records with an interval of 30 seconds between each record. This setting corresponds to a 200-minute period of observation, which includes the time required to recharge the battery. The actual period of observation should be shorter.

In the *Record Settings* window of the *Options* menu, select *Voltage*, *Energy*, *Current*, and *Time Data* as parameters to record.

8. In the *Four-Quadrant Dynamometer/Power Supply* window, start the *Battery Discharger* then immediately start the timer in the *Data Table* window.

Depending on the state-of-charge of the battery at the beginning of the discharge, the discharge cycle may end before the discharge duration (30 min) has elapsed if the cutoff voltage is attained. Stop the timer as soon as the discharge duration has elapsed or the cutoff voltage is attained.

9. Record the energy released by the battery (indicated by the meter *Energy* in the Four-Quadrant Dynamometer/Power Supply window) during the discharge cycle.

   Energy released during discharge: _______ Wh

   Energy released during discharge: 13.5 Wh.

10. Wait at least 30 minutes for the battery's chemical reaction to stabilize before proceeding with the next step.

Battery charge

11. In the Four-Quadrant Dynamometer/Power Supply window, modify the settings as follows:

    – Select the *Lead-Acid Battery Charger (Fast)* function.

    – Set the *Maximum Charge Current* to 0.92 A.

    – Set the *Gassing Voltage* to 14.4 V.

    – Set the *0.1C Current* to 0.23 A.

    – Set the *Float Voltage* to 13.8 V.

    Do not reset the meter Energy.

12. In the Four-Quadrant Dynamometer/Power Supply window, start the *Lead-Acid Battery Charger (Fast)* then immediately start the timer in the Data Table window.

13. While the battery is charging, briefly describe the charging process steps by referring to the parameters that you have set.

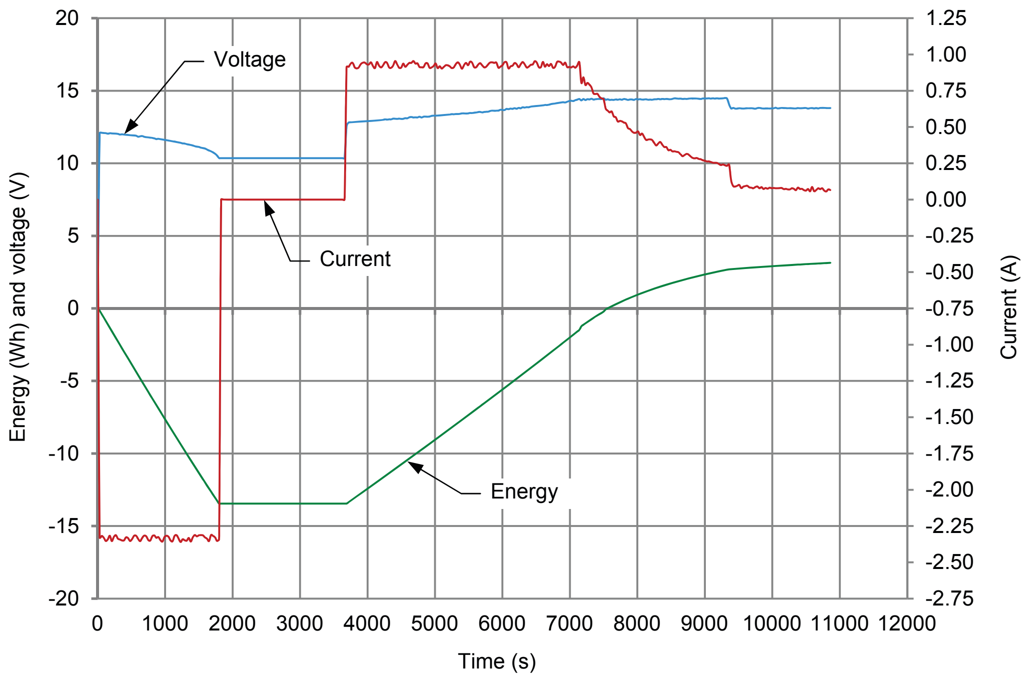
    While the battery continues to charge, it is suggested that you answer the review questions of this exercise.

    At the beginning of the charging process, the charge current applied to the battery is 0.92 A as set by the *Maximum Charge Current* parameter. This causes the battery voltage to gradually increase until it attains 14.4 V as set by the *Gassing Voltage* parameter. At this moment, the charge current starts to decrease while the battery voltage remains at 14.4 V until the charge current attains 0.23 A as set by the 0.1*C* *Current* parameter. Once the charge current is 0.23 A, the battery voltage is reduced to 13.8 V as set by the *Float Voltage* parameter to complete and maintain the battery charge.

14. Once the charge current is 0.23 A and the battery voltage is reduced to 13.8 V, let the battery charge for 20 min then stop the *Lead-Acid Battery Charger (Fast)*, then stop the timer in the Data Table window.

Save your data, export it to a spreadsheet application and plot the graph of the battery voltage, current, and energy versus time.

It is suggested that you include the data tables and graphs plotted in this exercise in your lab report.



Charge of a lead-acid battery using the modified constant-voltage charging method (fast charge).

15. You may have observed that the energy returned to the battery exceeded the energy released by the battery during the discharge cycle. Explain why.

Although the battery charging process is highly efficient, it is not 100% efficient.

16. By referring to the graph plotted in step 14, determine the time taken to return the energy released by the battery during the discharge cycle.

Approximately 3870 s.

17. Compare the energy returned to the battery at the moment where the gassing voltage is attained to the energy released during the discharge cycle. How do the energy values compare?

During this portion of the charge cycle, approximately 88% of the energy released during discharge has already been returned to the battery.

18. From the point where the charging current starts to decrease gradually as the voltage across the battery is kept near the gassing voltage value, does the energy continue to be returned to the battery and approach the energy released during discharge?

❑ Yes ❑ No

Yes

19. By referring to the graph plotted in step 14, describe how the charge current varies before the battery voltage attains the gassing voltage.

The charge current is constant at the value set by the *Maximum Charge Current* parameter (0.92 A).

20. If time allows, wait 30 min after the end of the charge cycle, then determine the current state-of-charge of the battery (expressed in percentage) by measuring the open-circuit voltage.

State-of-charge of the battery: _______%

State-of-charge of the battery: 100%.

Battery charge using the float charging method (slow charge)

Since the float charging method lasts several hours (typically 10 to 12 hours), it cannot be performed within a normal lab session. For this reason, it should be considered optional.

In this part of the exercise you will first discharge the remaining fully-charged battery of the Lead-Acid Batteries module to approximately 20% or residual capacity. Then you will charge the battery using the float charging method. During this charge cycle, you will observe the battery voltage and current as well as the energy returned to the battery.

21. Replace the battery connected to the Four-Quadrant Dynamometer/Power Supply with the remaining battery (fully charged) of the Lead-Acid Batteries module.

Battery discharge

22. In the Four-Quadrant Dynamometer/Power Supply window, modify the settings as follows:

- Set the *Function* parameter to *Battery Discharger (Constant-Current Timed Discharge with Voltage Cutoff)*.
- Set the *Discharge Current* to 2.3 A (C_{20}).
- Set the *Discharge Duration* to 30 min.
- Set the *Cutoff Voltage* to 9.45 V.
- Reset the meter *Energy*.

23. In the Data Table window, open a new data table, and set the timer to make 1440 records with an interval of 30 seconds between each record. This setting corresponds to a 12-hour period of observation, you may set other parameters that best correspond to your period of observation.

In the *Record Settings* window of the *Options* menu, select *Voltage*, *Energy*, *Current*, and *Time Data* as parameters to record.

24. In the Four-Quadrant Dynamometer/Power Supply window, start the *Battery Discharger* then immediately start the timer in the Data Table window.

Depending on the state-of-charge of the battery at the beginning of the discharge, the discharge cycle may end before the discharge duration (30 min) has elapsed if the cutoff voltage is attained. Stop the timer and the *Battery Discharger* as soon as the discharge duration has elapsed or the cutoff voltage is attained.

25. Record the energy released by the battery (indicated by meter *Energy* in the Four-Quadrant Dynamometer/Power Supply window) during the discharge cycle.

Energy released during discharge: _______ Wh

Energy released during discharge: 13.7 Wh.

26. Wait at least 30 minutes for the battery's chemical reaction to stabilize before proceeding with the next step.

Battery Charge

27. In the Four-Quadrant Dynamometer/Power Supply window, set the *Function* parameter to *Lead-Acid Battery Float Charger*. Make sure the *Float Voltage* parameter is set to 13.8 V.

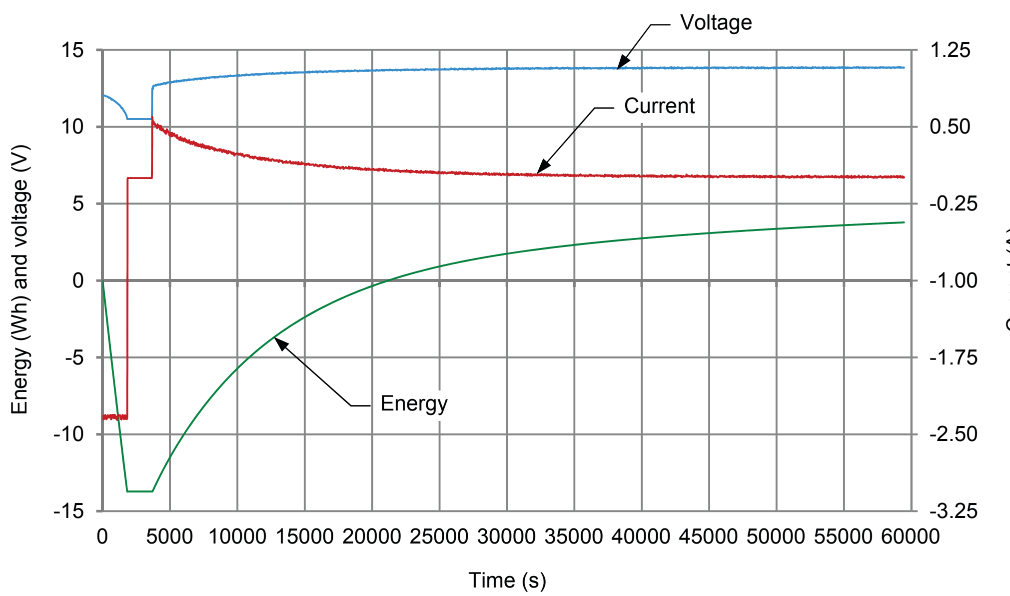
Do not reset the meter Energy.

28. Start the float charge by pressing the *Start/Stop* button in the Four-Quadrant Dynamometer/Power Supply window, then immediately start the timer in the Data Table window.

29. Once the charge cycle is ended (many hours later), stop the float charge by pressing the *Start/Stop* button in the Four-Quadrant Dynamometer/Power Supply window, and then stop the timer in the Data Table window.

Save your data, export it to a spreadsheet application, and plot the graph of the battery voltage, current, and energy versus time.

It is suggested that you include the data tables and graphs plotted in this exercise in your lab report.



Charge of a lead-acid battery using the float charging method.

30. At the end of the float charge, does the energy returned to the battery equal or exceed the energy released during the discharge at 20% of residual capacity?

❑ Yes ❑ No

Yes

31. If time allows, wait 30 min after the end of the charge cycle, then determine the current state-of-charge of the battery (expressed in percentage) by measuring the open-circuit voltage.

State-of-charge of the battery: _______%

State-of-charge of the battery: 100%.

32. By referring to the recorded data, compare the time taken to return 100% of the energy to the battery using the float charge method with the time taken to return 100% of the energy to the battery using the modified constant-voltage charging method. Does your comparison confirm that the modified constant-voltage charging method is a more rapid method of battery charging?

❑ Yes ❑ No

Yes

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

Conclusion

In this exercise, you were introduced to a number of methods for charging lead-acid batteries. You learned that in the modified constant-voltage charging method (fast charging), a constant current is first applied to the battery until a certain voltage is attained, and then the battery charging continues with a constant voltage until the current decreases to a value of $0.1C$. At this moment, the voltage is reduced to the float voltage value to complete and maintain the battery charge. In the float charging method, a constant voltage set to a value just sufficient to finish the battery charge or to maintain the full charge is applied to the battery. In the trickle charging method, a low-value current is applied to the battery. This low-value current is sufficient to maintain the full charge of a battery or to restore the charge of a battery that is used intermittently for short periods of time.

Review Questions

1. In which applications is the float charging method commonly used?

The float charging method is commonly used to maintain the charge of lead-acid batteries used in stationary applications.

2. What will the effect be of increasing the initial constant current and constant voltage on the charge time when charging a battery using the modified constant-voltage charging method?

   The higher the initial constant current and constant voltage the shorter the charge time will be.

3. Give another name for the trickle charging method.

   Compensating charge.

4. Which charging method is considered as a fast charging method?

   Modified constant-voltage charging method.

5. Which charging method should be used to maintain the charge of a stored battery (the battery is not connected to the load)?

   Trickle charging method.

Bibliography

Linden, David, and Reddy, Thomas B., *Handbook of Batteries*, 3d ed. New York: McGraw-Hill, 2002, ISBN 0-07-135978-8.