Electricity and New Energy

Wind Power Systems

Course Sample

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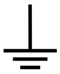
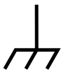
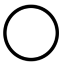
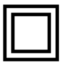
Safety and Common Symbols

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 electric shock
	Caution, hot surface
	Caution, risk of danger. Consult the relevant user documentation.
	Caution, lifting hazard
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation
	Consult the relevant user documentation.
	Direct current
	Alternating current

Safety and Common Symbols

Symbol	Description
	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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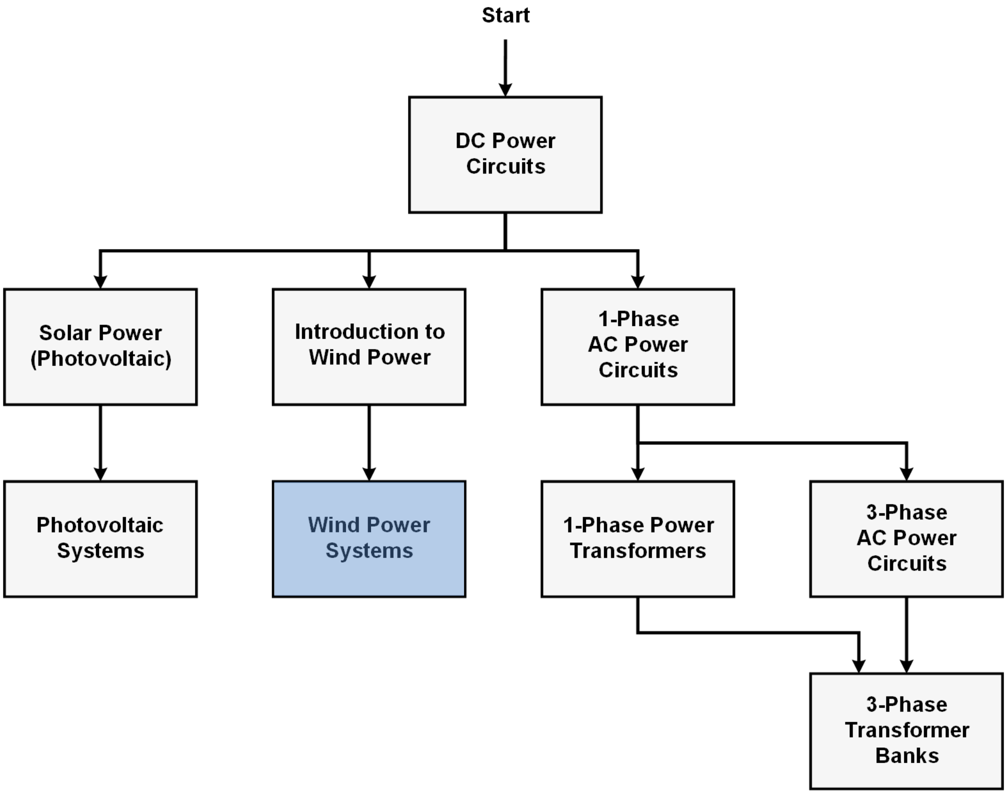
Preface

Electrical energy is part of our life since more than a century and the number of applications using electric power keeps increasing. This phenomenon is illustrated by the steady growth in electric power demand observed worldwide. In reaction to this phenomenon, the production of electrical energy using renewable natural resources (e.g., wind, sunlight, rain, tides, geothermal heat, etc.) has gained much importance in recent years since it helps to meet the increasing demand for electric power and is an effective means of reducing greenhouse gas (GHG) emissions.

To help answer the increasing needs for training in the wide field of electrical energy, Festo Didactic developed a series of modular courses. These courses are shown below as a flow chart, with each box in the flow chart representing a course.



Festo Didactic courses in electrical energy.

Teaching includes a series of courses providing in-depth coverage of basic topics related to the field of electrical energy such as dc power circuits, ac power circuits, and power transformers. Other courses also provide in-depth coverage of solar power and wind power. Finally, two courses deal with photovoltaic systems and wind power systems, with focus on practical aspects related to these systems.

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

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Course

Climate changes observed throughout the world in recent years have led to an ever-growing demand for renewable sources of energy to counteract these changes and to help minimize their negative effects on our lives. Wind power is one of the most important sources of renewable energy available on Earth. In certain countries, electricity produced from wind power fulfills a significant part of the total current energy demand.

The present course discusses wind power systems, i.e., systems that convert wind power into electric power which can be used to power electrical equipment or feed the local ac power network. The course covers the major aspects of stand-alone wind power systems, paying special attention to the integration of the major components used in these systems. Applications of stand-alone wind power systems are presented in the course. Finally, the course demonstrates the impact of using energy-efficient equipment on the size and cost of the stand-alone wind power system required in any specific application.

Home equipped with a wind power system converting wind into electricity.

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.

About This Course

Before performing manipulations with the equipment, you should read all sections regarding safety in the Safety Instructions and Commissioning manual accompanying the equipment.

Prerequisite

As a prerequisite to this course, you should have completed courses *DC Power Circuits* and *Introduction to Wind Power*.

Systems of units

Units are expressed using the International System of Units (SI).

To the Instructor

You will find in this Instructor version of the course all the elements included in the Student version of the course 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 and use

In order for students to be able to safely perform the hands-on exercises in this course, the equipment must have been properly installed, i.e., according to the instructions given in the accompanying Safety Instructions and Commissioning manual. Also, the students must familiarize themselves with the safety directives provided in the Safety Instructions and Commissioning manual and observe these directives when using the equipment.

Sample

Extracted from

Instructor Guide

Stand-Alone Wind Power Systems for DC Loads

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the configuration and operation of stand-alone wind power systems for dc loads. You will be able to verify that the charge controller, battery, and load controller selected for a specific stand-alone wind power system can work together without causing problems. You will understand how battery charging control is achieved in charge controllers. You will know how battery overdischarge protection works in load controllers. You will know common applications of stand-alone wind power systems for dc loads. Finally, you will understand that using energy efficient electric equipment is a means of reducing the size and cost of the stand-alone wind power system for dc loads required in any application.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to stand-alone wind power systems for dc loads
  Wind turbine. Rectifier. Battery. Charge controller. Load controller.
- Physical representation of a stand-alone wind power system for dc loads
- Operation of a stand-alone wind power system for dc loads
- Selection of the charge controller, battery, and load controller for a specific stand-alone wind power system for dc loads
- Stand-alone wind power system for dc loads implemented using a diversion charge controller
- Stand-alone wind power system for dc loads implemented using an MPPT wind power charge controller
- Applications of stand-alone wind power systems for dc loads
  Electric power provision in small buildings. Electric power provision in small boats. Battery charging in recreational vehicles.
- Effect of using energy-efficient electric equipment on the size and cost of stand-alone wind power systems for dc loads

DISCUSSION

Introduction to stand-alone wind power systems for dc loads

Figure 4 shows a simplified diagram of a stand-alone wind power system for dc loads. The system consists of a wind turbine, a rectifier, a charge controller, a battery, and a load controller.

Several elements, such as the wind turbine lightning surge arrestor, wind turbine disconnect/stop switch, disconnect switches, and fuses, have been omitted in the simplified diagram below for the sake of clarity.

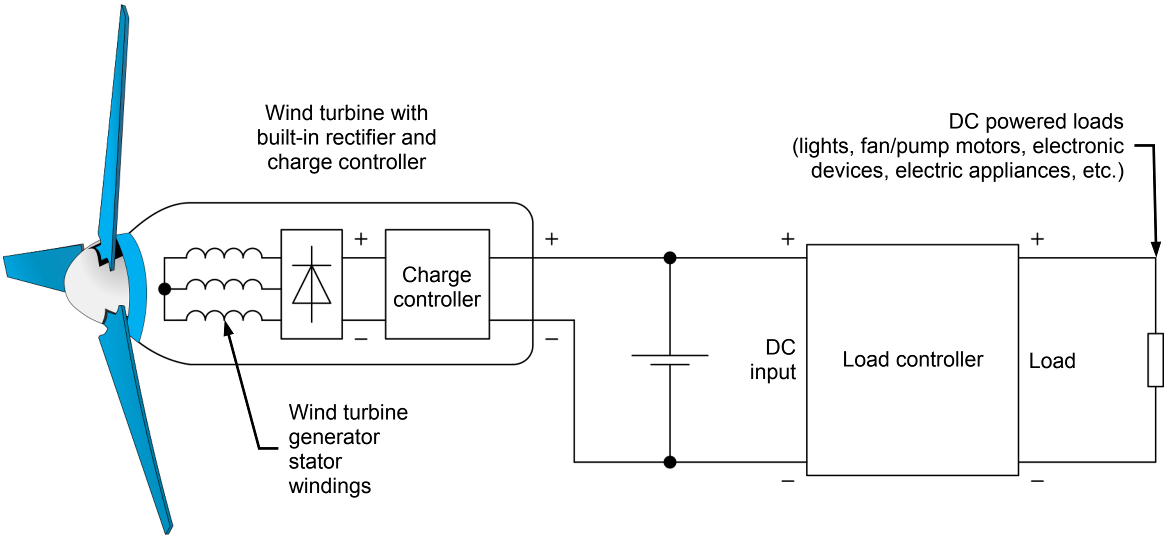


Figure 4. Simplified diagram of a stand-alone wind power system for dc loads implemented using a wind turbine with built-in rectifier and charge controller.

Notice that the rectifier and the charge controller are built in the wind turbine in the wind power system of Figure 4. This configuration minimizes the number of components in the system. For each of the element in this system, the remaining of this section states the function of the element, describes what the element consists of, and briefly explains how the element operates.

Other configurations are possible for stand-alone wind power systems for dc loads. Two other common system configurations are briefly presented later in this discussion.

Wind turbine

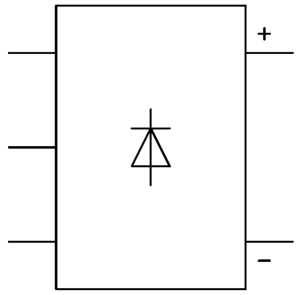
The wind turbine is basically a three-phase synchronous generator with a bladed rotor, mounted atop a mast. In most cases, a permanent magnet synchronous generator is used in small wind turbines. In the simplified diagram of Figure 4, the wind turbine also includes a rectifier and a charge controller. These elements are described later in this section of the discussion.

The wind turbine generator converts wind power into electric power. The electric power takes the form of three-phase ac power which is made available through the stator windings of the wind turbine generator.

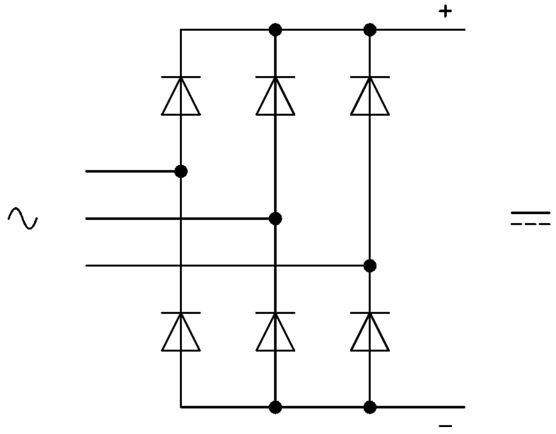
A single wind turbine is often sufficient in applications where the **daily energy demand** is low. On the other hand, several wind turbines may be required in applications where the daily energy demand is larger. Determining the size (power) of the wind turbine(s) required in a specific stand-alone wind power system mainly depends on the daily energy demand (kWh / day) and the average value of the wind power available at the location the system is installed. It also depends on other parameters of lesser importance and is a fairly complex process which is beyond the scope of this course.

Rectifier

The rectifier converts the three-phase ac power produced by the wind turbine generator into dc power. The rectifier is a 5 terminal, power electronic device which consists of six power diodes arranged to form a three-phase bridge rectifier, as shown in Figure 5.



(a) symbol



(b) diagram

Figure 5. Symbol and diagram of a three-phase diode bridge rectifier.

Battery

An array of batteries is commonly referred to as a battery bank.

The battery stores electricity produced by the wind turbine. It consists of a single battery in low power applications, or an array of batteries connected in series, in parallel or in series-parallel in applications requiring more power. Deep-cycle, lead-acid batteries are generally used in stand-alone wind power systems because they can be discharged repeatedly to a large percentage (generally up to 80%) of their rated capacity without harm, although such repetitive deep discharges will likely shorten the battery lifetime. Deep-cycle, lead-acid batteries are also commonly used in stand-alone wind power systems because they are cost effective.

The nominal voltage of the battery or battery bank in a stand-alone wind power system is generally 12 V, 24 V or 48 V. The battery voltage sets the voltage at which the wind power system operates, and thus, is commonly referred to as the system voltage. Figure 6 shows typical arrangements of battery banks resulting in system voltages of 12 V, 24 V, and 48 V.

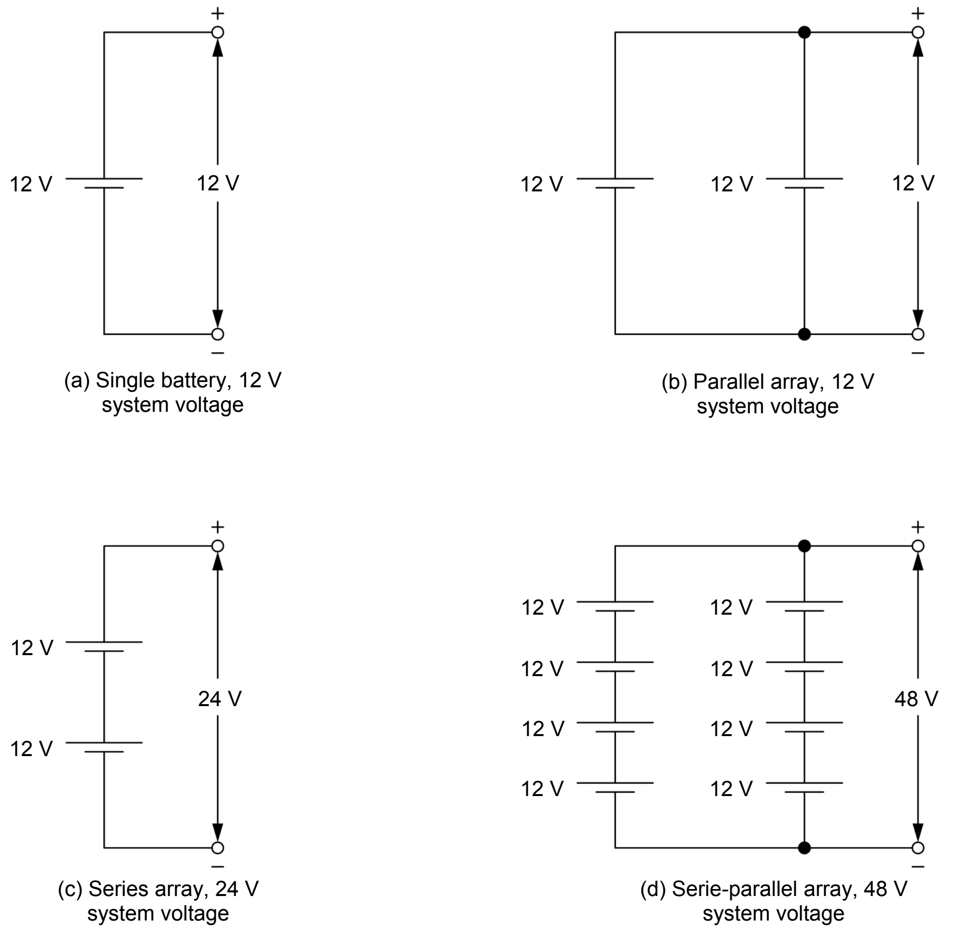


Figure 6. Typical arrangements of battery banks resulting in system voltages of 12 V, 24 V, and 48 V.

Connecting batteries in series increases the system voltage. Connecting batteries in parallel increases the system capacity (Ah), i.e., the amount of electricity that the stand-alone wind power system can store. The larger the storage capacity, the longer the wind power system can continue to supply power to the loads when the wind turbine produces no or little electricity. The parameters listed below are the key factors used to determine the capacity (Ah) of the battery or battery bank required in a specific stand-alone wind power system.

- Daily energy demand (kWh/day) of the loads.
- Average value of the wind power available at the location the wind power system is installed.
- Desired system autonomy, i.e., the period (generally a given number of days) during which the stand-alone wind power system should be able to supply power to the loads without the wind turbine producing electricity.

Determining the capacity (Ah) of the battery required in a stand-alone wind power system also depends on other parameters of lesser importance and is a fairly complex process which is beyond the scope of this course.

Charge controller

The **charge controller** is a power control device that controls battery charging to prevent the battery from being overcharged. The charge controller also keeps the wind turbine generator loaded at all times to prevent rotation at excessive speeds. Finally, the charge controller in the diagram of Figure 4 makes the wind turbine operate at the **maximum power point (MPP)**, i.e., at the specific combination of speed and torque at which the wind turbine produces the maximum amount of power at a given wind speed. This feature, which is referred to as **maximum power point tracking (MPPT)**, ensures that the maximum current possible charges the battery at any wind speed.

The charge controller uses electronic circuitry and power switching devices to achieve the various functions mentioned above. In fact, it is the “intelligent” device around which any stand-alone wind power system is built. The remaining of this section describes how the charge controller performs MPP tracking (MPPT), battery charging control, and overspeed prevention.

To achieve MPPT, the charge controller adjusts the electrical load applied to the wind turbine generator to maintain the speed and torque at the wind turbine rotor as close as possible to the values required to produce the maximum amount of mechanical power possible at the current wind speed. To adjust the electrical load applied to the generator, the charge controller sets the average value of the current flowing at its output using a technique called **pulse-width modulation (PWM)**. Figure 7 shows how PWM is used to vary the average value of a current. PWM uses pulses of current instead of a continuous current. Adjusting the width of the current pulses allows the average value of current to be changed. Large changes in the width of the current pulses are used in the example of Figure 7. This results in large step variations in the average value of the current that clearly demonstrate the effect which changing the width of the current pulses produces. Gradual variation of the average value of the current can be achieved by slightly varying the pulse width from one pulse of current to the next. Note that the average value of current can be adjusted to any value up to the amplitude A of the current pulses.

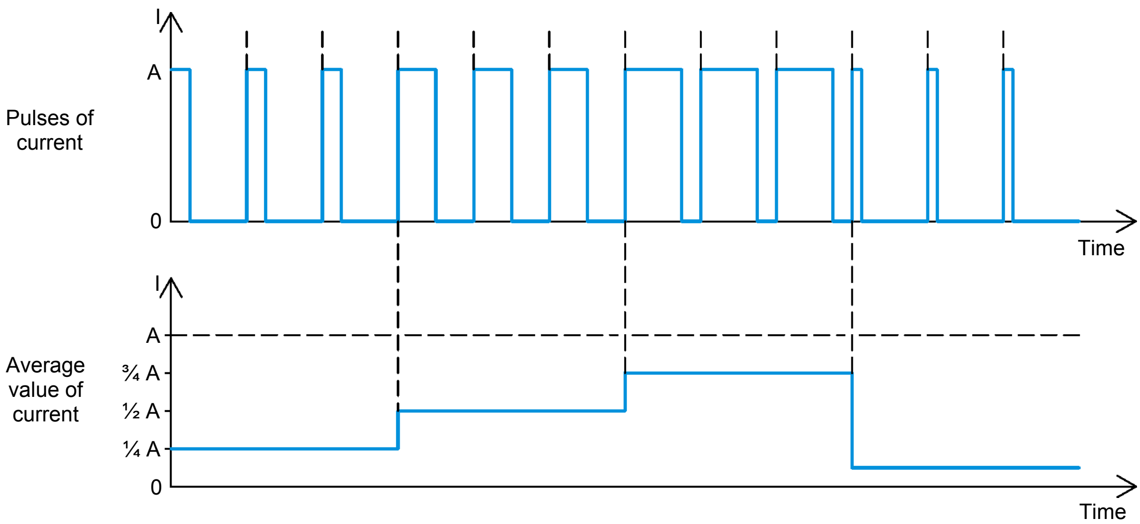


Figure 7. Use of pulse-width modulation (PWM) to vary the average value of a current.

A charge controller that performs on-off charge control is referred to as an on-off charge controller.

To achieve battery charging control, the charge controller simply stops battery charging when the battery voltage reaches a certain value, called voltage regulation (VR) setpoint, at which the battery is considered to be fully charged. The charge controller resumes battery charging when the battery voltage decreases to a certain value, called voltage regulation reconnect (VRR) setpoint. This type of battery charging control is referred to as on-off charge control. Battery charging using on-off charge control is illustrated in Figure 8.

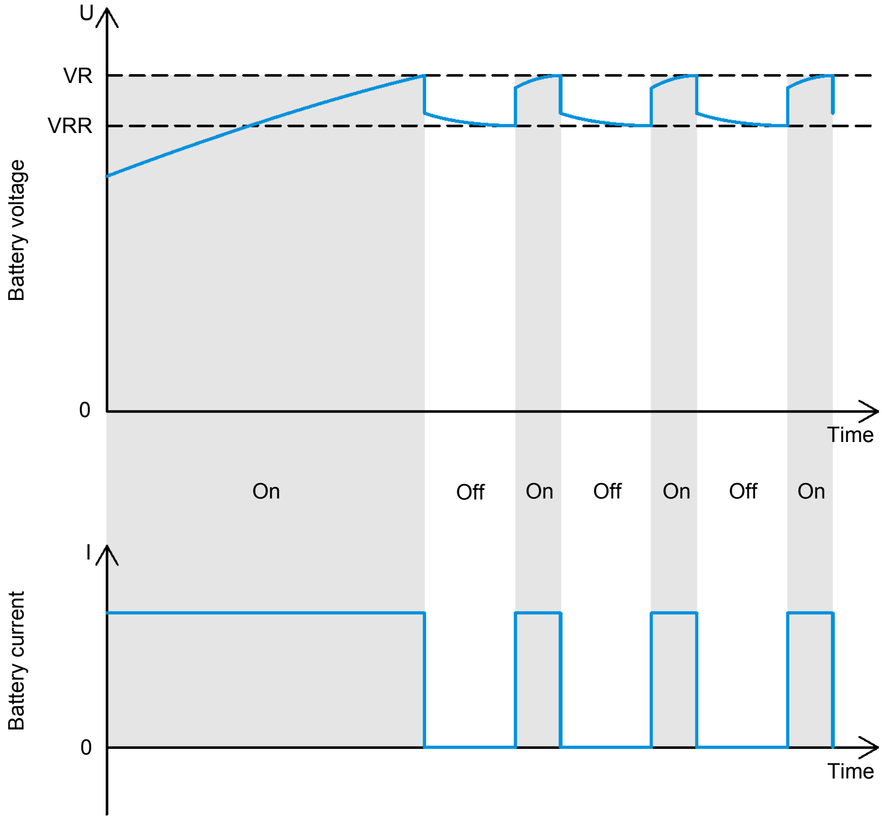


Figure 8. Battery charging using on-off charge control.

Table 1 shows typical values of the VR and VRR setpoints that can be used with on-off charge control for various types of lead-acid batteries commonly available on the market. The values presented are for 12 V batteries. The values of the VR and VRR setpoints which on-off charge control uses to charge the battery whenever required are those given under the heading *Normal charge* in the table. Every 10 to 20 days, some charge controllers perform an equalization charge of the battery. An equalization charge is simply a charging cycle that slightly overcharges the battery to equalize the state-of-charge of the battery cells. For this purpose, the values of the VR and VRR setpoints used during an equalization charge (see heading *Equalization charge* in the table) are slightly higher than those used during a normal charge.

In charge controllers that do not have the charge equalization feature, the values of the VR and VRR setpoints used during a normal charge may be increased slightly (generally by about 0.3 V to 0.6 V).

Table 1.Typical values of the VR and VRR setpoints that can be used with on-off charge control for various types of 12 V lead-acid batteries.

Type of lead-acid battery	Normal charge		Equalization charge	
	VR (V)	VRR (V)	VR (V)	VRR (V)
Flooded, vented	14.4	13.5	15.3	14.1
Flooded, sealed	14.4	13.5	15.0	13.8
AGM	14.1	13.2	14.4	13.5
GEL	14.1	13.2	14.7	13.5

The values of the VR and VRR setpoints used in a particular charge controller are normally indicated in the documentation provided by the manufacturer.

Note that on-off charge control has no control on the value of the battery charging current. Consequently, this limits battery charging performance and may reduce battery life. In fact, with on-off charge control, the value of the battery charging current is equal to the charge controller output current minus the load current. Neither the charge controller output current nor the load current is set so as to optimize the battery charging current. The average value of the charge controller output current is adjusted by the MPPT algorithm of the charge controller to set the electrical load applied to the wind turbine generator to the value required for maximum power production, as explained earlier in this section. On the other hand, the value of the load current depends on the dc loads that are in use.

Also note that to stop battery charging, the charge controller short-circuits its output, without short-circuiting the battery. In fact, this is equivalent to short-circuiting the wind turbine generator output. This causes the electrical load applied to the wind turbine generator to increase markedly, thereby producing a strong braking torque at the wind turbine rotor and a sharp decrease in the rotor speed. Short-circuiting the wind turbine generator output when the battery is fully charged keeps the wind turbine loaded, thereby preventing the wind turbine rotor from rotating at excessive speeds. If battery charging were stopped by simply disconnecting the output of the charge controller from the battery and the load controller, the wind turbine would be left without electrical load and the rotor speed would likely increase to excessive values (especially when wind is strong). This would eventually cause damage to the wind turbine. Consequently, keeping a wind turbine loaded at all times is an essential feature of the charge controller to avoid damage caused by rotation at excessive speeds.

Load controller

The **load controller** prevents overdischarge of the battery by disconnecting the load when the battery voltage decreases down to a certain value, called the low-voltage disconnect (LVD) setpoint. The controller automatically reconnects the load when the battery voltage increases up to a certain value, called the low-voltage reconnect (LVR) setpoint. Battery overdischarge protection is illustrated in Figure 9.

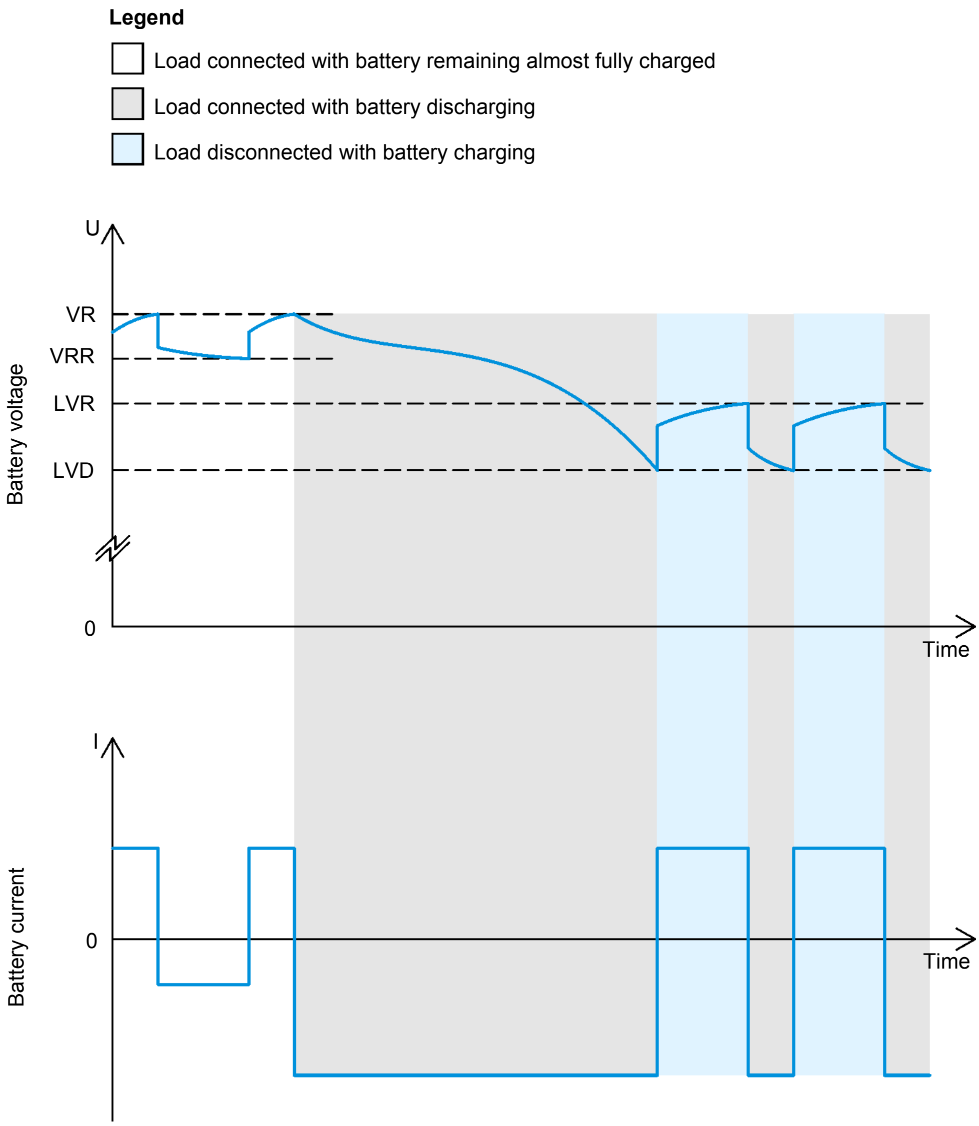


Figure 9. Battery overdischarge protection.

The value of the LVD setpoint mainly depends on the maximum depth of discharge (DOD) recommended by the battery manufacturer. The value of the LVD setpoint is also influenced by the value of the discharge current that is expected. This is because the battery internal resistance makes the voltage across the battery decrease as the value of the discharge current increases. Table 2 shows approximate values of the LVD setpoint that can be used to implement battery overdischarge protection for different values of maximum DOD and discharge rate (i.e., discharge current expressed as a function of the battery capacity C). The values presented are for 12 V batteries. The higher the maximum DOD value that is acceptable, the lower the value of the LVD setpoint. Also, for any maximum DOD value, the higher the discharge rate expected, the lower the value of the LVD setpoint.

Table 2. Approximate values of the LVD setpoint that can be used to implement battery overdischarge protection for different values of maximum DOD and discharge rate (12 V batteries).

Maximum DOD	LVD setpoint			
(%)	@ C/200 (V)	@ C/60 (V)	@ C/20 (V)	@ C/10 (V)
20	12.8	12.7	12.5	12.4
30	12.7	12.6	12.4	12.3
40	12.5	12.5	12.3	12.2
50	12.4	12.3	12.2	12.1
60	12.2	12.1	12.0	11.9
70	12.0	11.9	11.9	11.8
80	11.8	11.8	11.7	11.5

The value of the LVR setpoint is mainly governed by the minimum state of charge (SOC) that the battery should recover before the load is reconnected. The value of the LVR setpoint is also influenced by the value of the charge current that is expected. This is because the battery internal resistance makes the voltage across the battery increase as the value of the charge current increases. Table 3 shows approximate values of the LVR setpoint that can be used to implement battery overdischarge protection for different values of minimum SOC and charge rate (i.e., charge current expressed as a function of the battery capacity C). The values presented are for 12 V batteries. The higher the minimum SOC value that is required before the load is reconnected, the higher the value of the LVR setpoint. Also, for any minimum SOC value, the higher the charge rate expected, the higher the value of the LVR setpoint.

Table 3. Approximate values of the LVR setpoint that can be used to implement battery overdischarge protection for different values of minimum SOC and charge rate (12 V batteries).

Minimum SOC	LVR setpoint			
(%)	@ C/200 (V)	@ C/60 (V)	@ C/20 (V)	@ C/10 (V)
30	12.5	12.6	12.8	12.9
40	12.7	12.8	13.0	13.1
50	12.9	13.0	13.3	13.4
60	13.2	13.3	13.5	13.6
70	13.5	13.6	13.9	14.0
80	13.9	14.0	14.5	14.6

In brief, the values of the LVD and LVR setpoints in the charge controller should be set according to the maximum DOD and minimum SOC values that are desired as well as the values of the discharge current and charge current that are expected in the application considered.

Physical representation of a stand-alone wind power system for dc loads

Figure 10 is an example of the physical representation of a stand-alone wind power system for dc loads.

Several elements, such as the wind turbine lightning surge arrestor, wind turbine disconnect/stop switch, disconnect switches, and fuses, have been omitted in the simplified representation below for the sake of clarity.

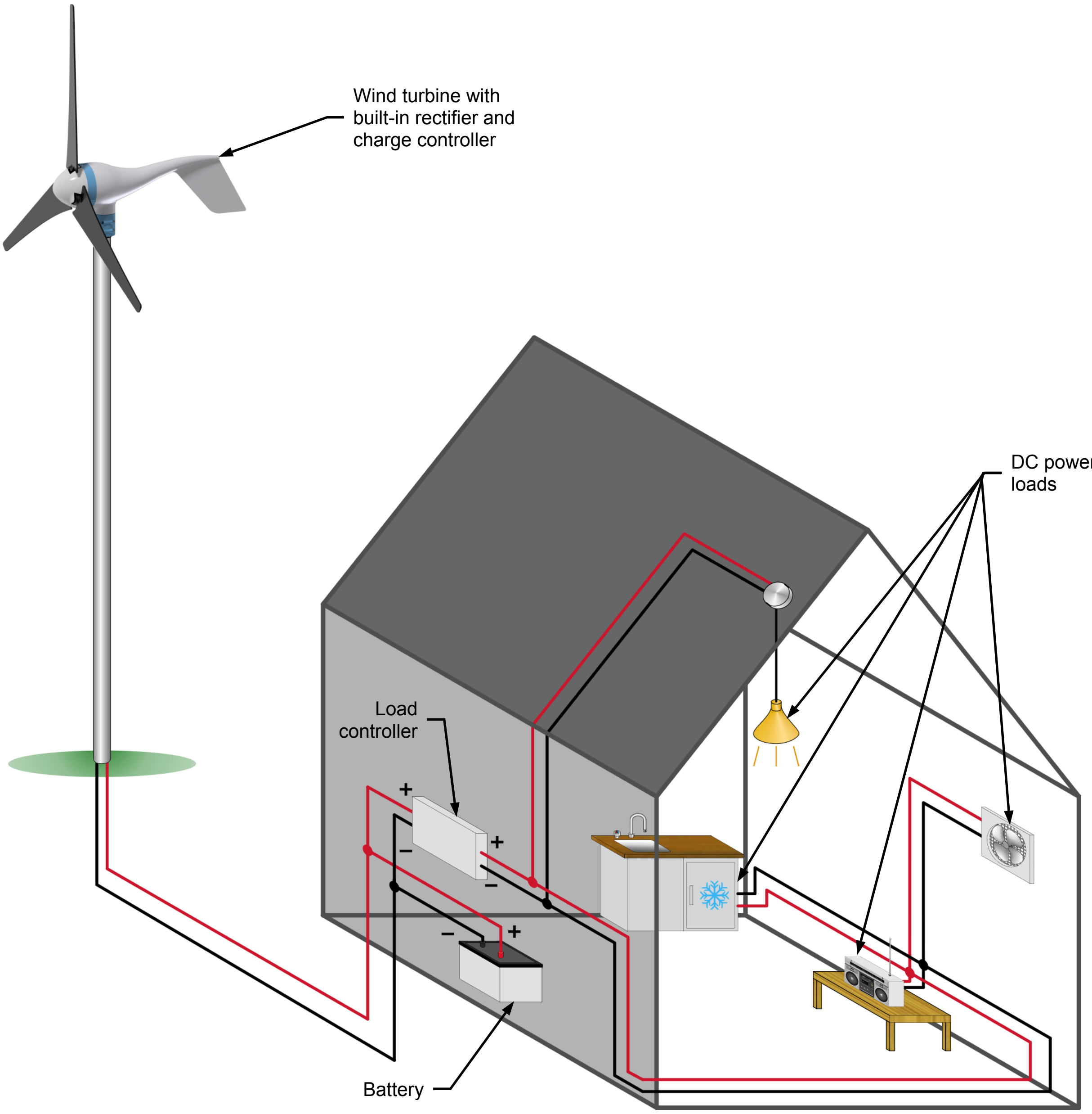


Figure 10. Simplified physical representation of a stand-alone wind power system for dc loads.

In this example, the wind turbine is installed atop a mast located close to a building. To avoid disturbances caused by noise produced by the rotor of the wind turbine, the mast is installed at a certain distance from the building in certain applications. A wind turbine with built-in rectifier and charge controller (as shown in the diagram of Figure 4) is used in this example. Two wires running through the mast and soil route dc power from the wind turbine to the building. The battery and the load controller are located inside the building so they are protected from weather. The battery is located as close as possible to the load controller in order to minimize the length of the interconnecting leads, and thus, the power losses in these leads. Note that because the wind turbine is installed outdoors, the leads connecting the wind turbine to the battery are long (i.e., much longer than the leads connecting the battery to the load controller). Consequently, these leads must be sized properly (i.e., a sufficient wire gauge must be used) to limit the power losses in these leads.

Operation of a stand-alone wind power system for dc loads

A stand-alone wind power system for dc loads operates as follows. When wind is strong enough, the wind turbine produces electricity that is routed to the battery and the load controller. When the wind turbine produces electricity at a rate that is below the power demand of the dc loads, electricity is drawn from the battery to meet the power demand, as shown in Figure 11. The battery discharges slowly as it supplies power to the dc loads, thereby causing the battery voltage ($U_{Batt.}$) to decrease gradually. When the battery voltage decreases down to the LVD setpoint, the load controller automatically disconnects the dc loads to prevent the battery from being discharged too deeply. Once the battery has recovered enough charge (i.e., when the battery voltage reaches the LVR setpoint), the load controller automatically reconnects the dc loads to the battery.

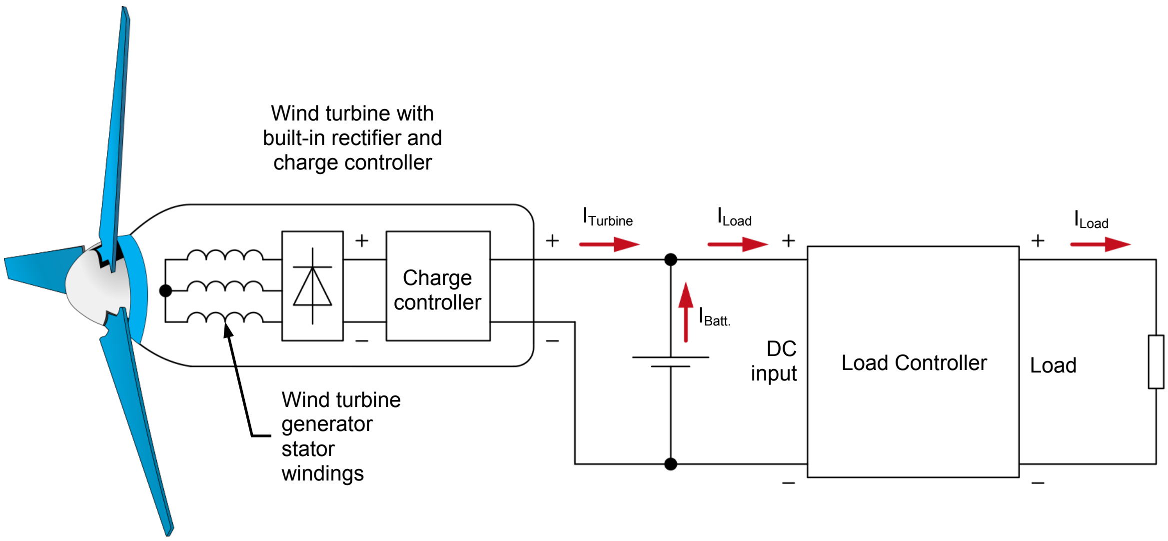


Figure 11. Operation of a stand-alone wind power system for dc loads when the wind turbine produces electricity at a rate that is below the power demand of the loads. Electricity is drawn from the battery to meet the power demand.

On the other hand, when the wind turbine produces electricity at a rate exceeding the power demand of the dc loads, the excess energy produced by the wind turbine charges the battery (when required), as shown in Figure 12.

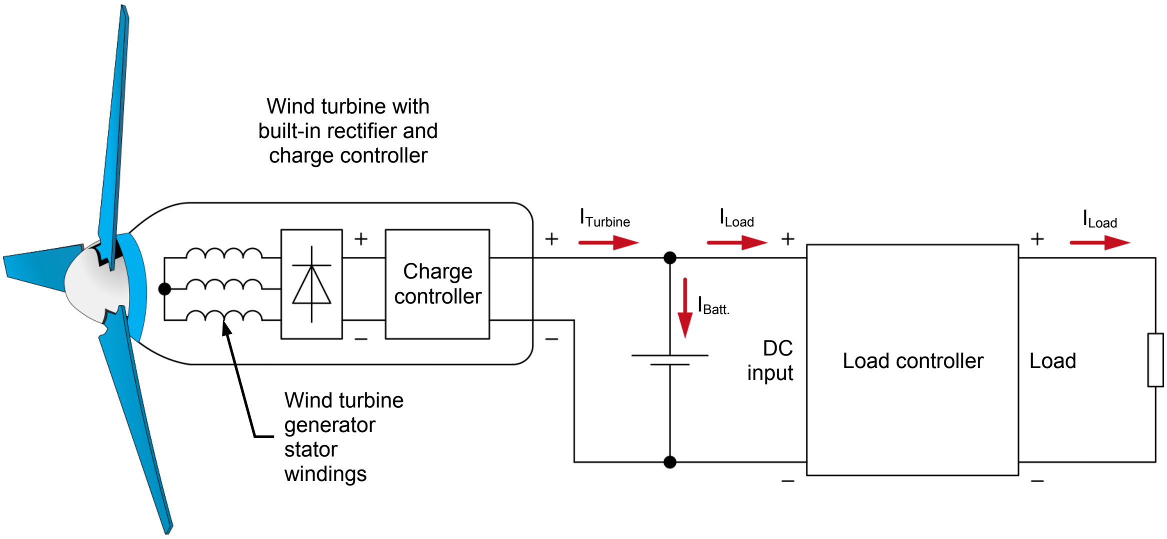


Figure 12. Operation of a stand-alone wind power system for dc loads when the wind turbine produces electricity at a rate exceeding the power demand of the loads. This allows the battery to be charged when required.

The charge controller automatically stops charging the battery as soon as it detects that the battery is fully charged, thereby preventing battery overcharging. Whenever the charge controller stops battery charging, the electricity required to meet the power demand of the dc loads all comes from the battery. Also, large currents flow through the wind turbine generator windings and the rectifier because the charge controller stops battery charging by short-circuiting its output (without short-circuiting the battery) to prevent the wind turbine from rotating at excessive speeds. This is shown in Figure 13.

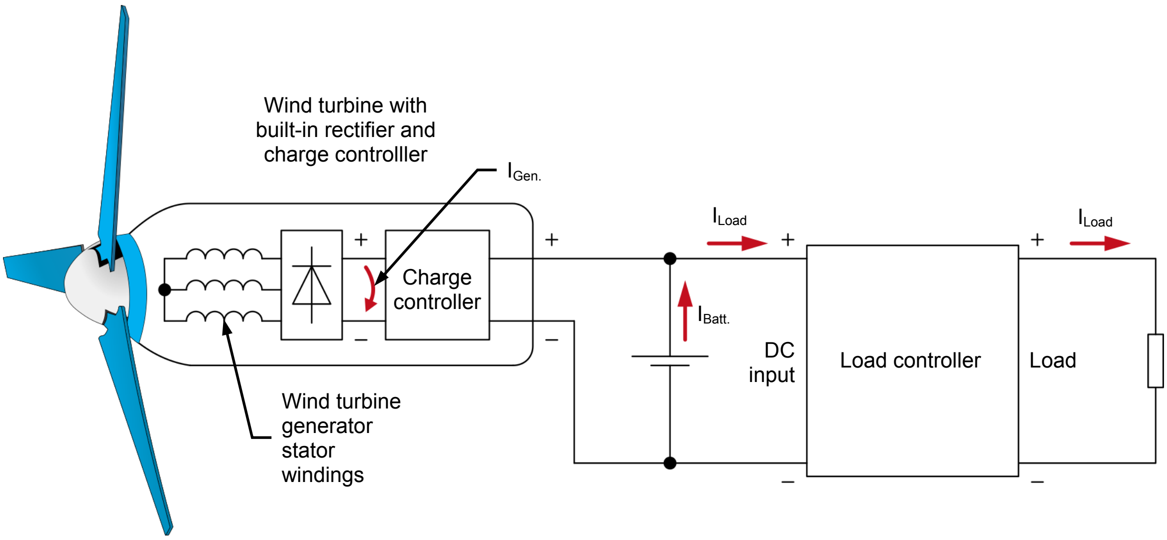


Figure 13. Operation of a stand-alone wind power system when the charge controller stops battery charging.

In brief, the charge controller and load controller are the centerpieces that manage power flow in any stand-alone wind power system to ensure efficient and reliable operation.

Selection of the charge controller, battery, and load controller for a specific stand-alone wind power system for dc loads

Table 4 presents the key specifications that must be considered to make sure that the charge controller, battery, and load controller in the stand-alone wind power system for dc loads shown in Figure 4 can work together without causing problems.

Table 4. Key specifications to be considered when making sure that the charge controller, battery, and load controller in the stand-alone wind power system for dc loads shown in Figure 4 can work together without causing problems.

Component	Specified parameter	Description of parameter
Charge controller	VR setpoint	Value of the VR setpoint in the charge controller.
Battery	Nominal voltage	Nominal voltage across the battery terminals.
Load controller	System (load) voltage	Nominal voltage across the dc input terminals and load terminals of the load controller.
	Maximum load current	Maximum load current that can flow through the load controller without causing overheating of the unit (and eventual damage to the unit).

The following steps must be performed to make sure that the charge controller, battery, and load controller in the stand-alone wind power system for dc loads shown in Figure 4 can work together without causing problems.

1. The VR setpoint of the charge controller must match the nominal voltage of the battery to achieve proper battery charging.

2. The nominal voltage of the battery must be the same as the system (load) voltage of the load controller. Naturally, all dc loads connected to the stand-alone wind power system must be designed to operate at this voltage.

3. The system (load) voltage and maximum load current of the load controller determine the maximum power that the stand-alone wind power system can supply to the dc loads. The power rating of any one of the dc loads connected to the system must not exceed the maximum power that the system can supply, otherwise overheating of the load controller will occur.

Stand-alone wind power system for dc loads implemented using a diversion charge controller

Figure 14 shows a simplified diagram of a stand-alone wind power system for dc loads implemented with a **diversion charge controller**.

Several elements, such as the wind turbine lightning surge arrestor, wind turbine disconnect/stop switch, disconnect switches, and fuses, have been omitted in the simplified diagram below for the sake of clarity.

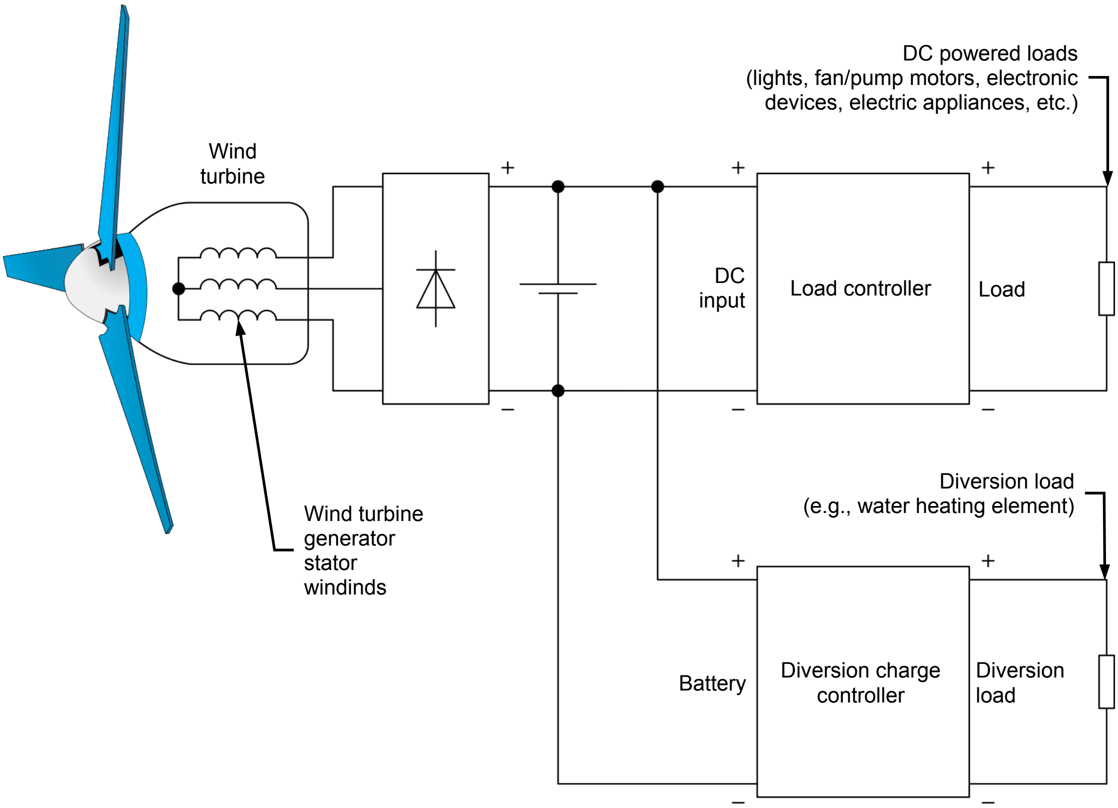


Figure 14. Simplified diagram of a stand-alone wind power system for dc loads implemented using a diversion charge controller.

The wind turbine, the diode rectifier, the battery, and the load controller in this system are the same as in the stand-alone wind power system for dc loads shown in Figure 4. Notice, however, that the rectifier is not built in the wind turbine. Also, notice that an external charge controller and a diversion load are used in the system of Figure 14 instead of a charge controller built in the wind turbine. Such charge controller is commonly referred to as a diversion charge controller.

When the wind turbine produces electricity at a rate exceeding the power demand of the dc loads, the diversion charge controller controls battery charging (i.e., adjusts the battery charging current) by gradually diverting more and more of the wind turbine current toward the diversion load as the battery charges. When the battery is fully charged, most of the wind turbine current flows through the diversion load. This way, the diversion load controller ensures that the wind turbine remains loaded at all times (even when the battery is fully charged), thereby preventing the wind turbine rotor from rotating at excessive speeds. The diversion load in such stand-alone wind power systems is often a water heating element. This allows any excess power produced by the wind turbine generator (i.e., electric power that is not required to charge the battery) to be used to heat water stored in a tank.

The diversion charge controller controls battery charging by gradually diverting the wind turbine current toward the diversion load, as mentioned above. The charge controller uses the PWM technique introduced earlier in this discussion to adjust the amount of current that is diverted toward the diversion load. Figure 15 illustrates how battery charging control takes place in the diversion charge controller. In fact, it is a generic battery charging process that consists of three phases named bulk, absorption, and float. This battery charging process is commonly referred to as modified constant-voltage charging. Modified constant-voltage charging provides better charge control than on-off charge control. This greatly helps in optimizing battery capacity as well as in maximizing battery life.

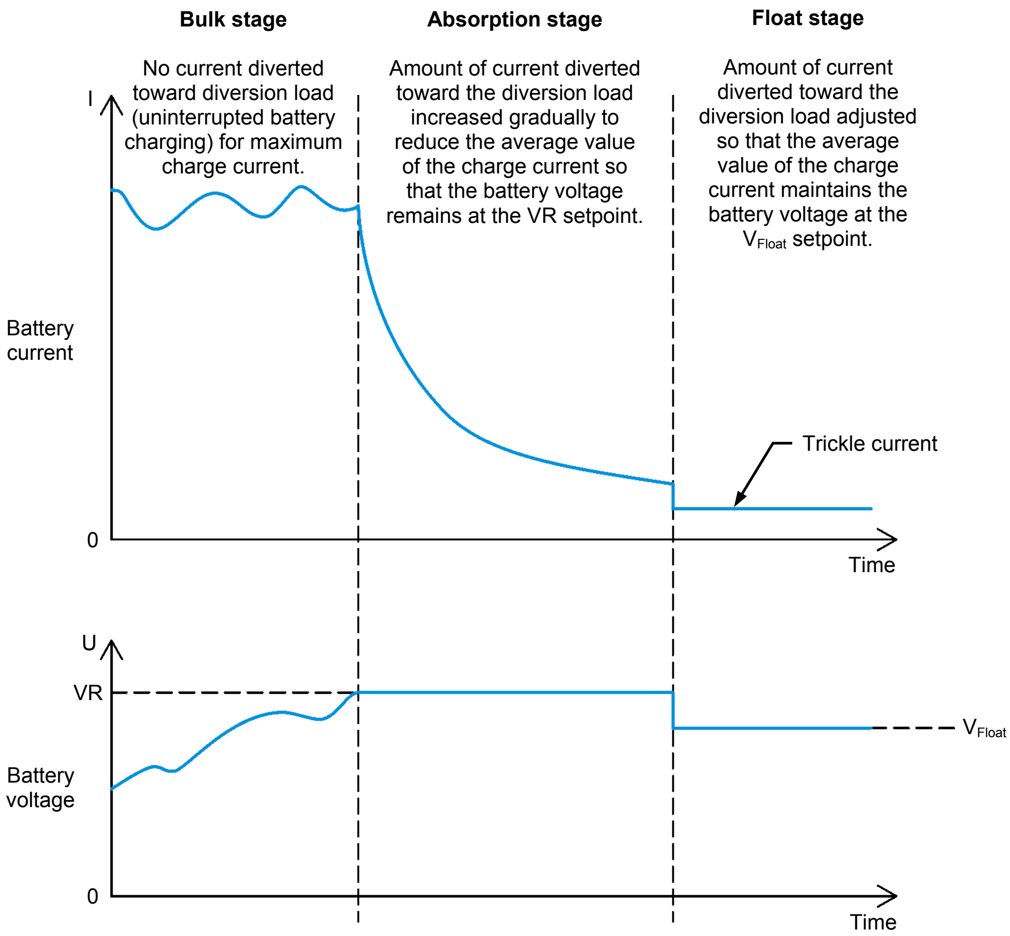


Figure 15. Modified constant-voltage charging used in diversion charge controllers.

Table 5 shows typical values of the VR and V_{Float} setpoints that can be used in diversion charge controllers for various types of lead-acid batteries commonly available on the market. The values presented are for 12 V batteries. The values of the VR and V_{Float} setpoints which the diversion charge controller uses to charge the battery whenever required are those given under the heading *Normal charge* in the table. Every 10 to 20 days, some diversion charge controllers perform an equalization charge of the battery. For this purpose, the value of the VR setpoint which the charge controller uses during an equalization charge (see heading *Equalization charge* in the table) is slightly higher than that used during a normal charge.

Table 5. Typical values of the VR and V_{Float} setpoints that can be used in diversion charge controllers for various types of 12 V lead-acid batteries.

Type of lead-acid battery	Normal charge		Equalization charge
	VR (V)	V_{Float} (V)	VR (V)
Flooded, vented	14.4	13.5	15.0
Flooded, sealed	14.7	13.8	15.0
AGM	14.1	13.5	14.4
GEL	14.4	13.5	14.7

Note that diversion charge controllers do not perform MPP tracking (MPPT). This is because the electrical load applied to the wind turbine generator in this case depends on the dc loads that are in use, the value of the current required to charge the battery, and the size of the diversion load.

Stand-alone wind power system for dc loads implemented using an MPPT wind power charge controller

Figure 16 shows a simplified diagram of a stand-alone wind power system for dc loads implemented with an **MPPT wind power charge controller**.

Several elements, such as the wind turbine lightning surge arrestor, wind turbine disconnect/stop switch, disconnect switches, and fuses, have been omitted in the simplified diagram below for the sake of clarity.

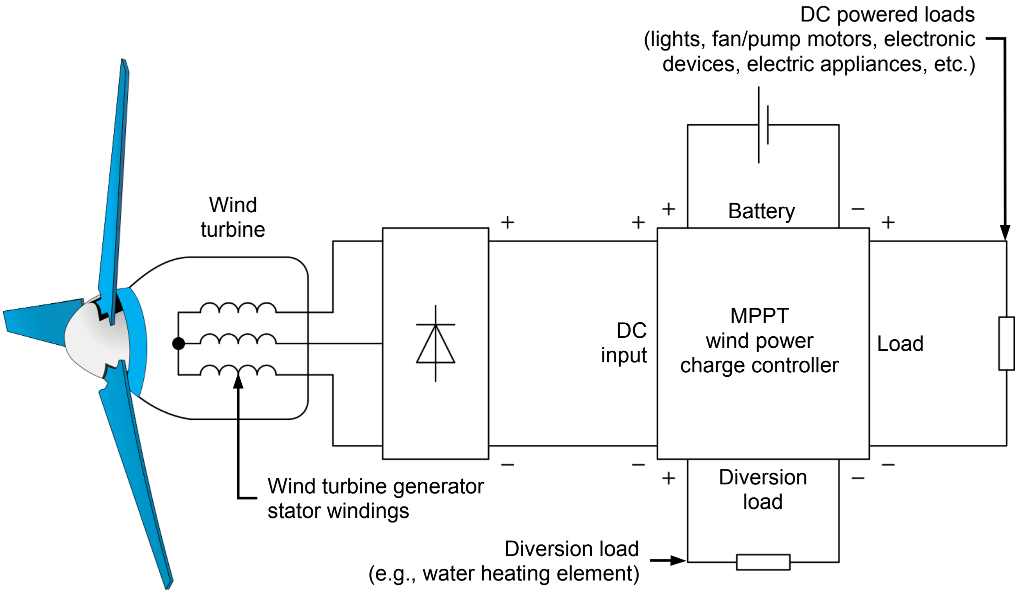


Figure 16. Simplified diagram of a stand-alone wind power system for dc loads implemented using an MPPT wind power charge controller.

The wind turbine, the diode rectifier, and the battery are the same as in the two stand-alone wind power systems for dc loads shown earlier in this discussion. However, an MPPT wind power charge controller is used in place of the charge controller and load controller used in these systems. The MPPT wind power charge controller is an electronic device that is specifically designed for stand-alone wind power systems. It combines all the functions of the charge controller and load controller used in the two stand-alone wind power systems discussed earlier. More specifically, the MPPT wind power charge controller performs the following four functions.

- Battery charging control (modified constant-voltage battery charging)
- MPP tracking (MPPT) when required, i.e., during the bulk phase of battery charging
- Prevents rotation at excessive speeds by keeping the wind turbine generator loaded at all times, using a diversion load when required
- Prevents battery overdischarge the same way as a load controller does

The use of modified constant-voltage battery charging helps in optimizing battery capacity as well as in maximizing battery life. Furthermore, MPP tracking ensures that the maximum current possible charges the battery when required, i.e., during the bulk phase of battery charging. In other words, the MPPT wind power charge controller combines the two best features of the charge controllers used in the stand-alone wind power systems for dc loads discussed earlier.

Applications of stand-alone wind power systems for dc loads

Stand-alone wind power systems for dc loads are used in a variety of applications. This section describes some common applications of stand-alone wind power systems for dc loads.

Electric power provision in small buildings

Stand-alone wind power systems for dc loads are commonly used to provide dc power to low-power electric equipment in small buildings that are not connected to the grid (e.g., farm buildings, green houses, etc.) or that are located in remote locations (e.g., hunting/fishing cabins, mountain refuges, etc.). The dc powered equipment in this type of application generally consists of low-power devices such as lighting fixtures, fan/pump motors, refrigerators, radios, etc.

Figure 17. Cabin powered by a stand-alone wind power system.

Electric power provision in small boats

Stand-alone wind power systems for dc loads can be used to provide dc power to low-power electric equipment in small boats (fishing boats, sailboats, etc.). The dc powered equipment in this type of application generally consists of low-power devices such as lights, fan/pump motors, radiocommunication equipment, navigation equipment, etc.

Figure 18. Sailboat equipped with a stand-alone wind power system.

Battery charging in recreational vehicles

Several low-power electrical devices (lighting fixtures, fan/pump motors, refrigerator, LP gas detector, etc.) in a recreational vehicle (RV) operate from dc power. A deep-cycle, lead-acid battery supplies dc power to these devices when the RV is not connected to an ac power outlet. A charge controller in the RV can use electricity produced by a wind turbine to supply dc power to these devices and keep the battery charged. In this case, the dc power system in an RV operates exactly like a stand-alone wind power system for dc loads. Note that when the RV is connected to an ac power outlet, the charge controller can draw power from the grid and convert it to dc power to supply the dc powered devices and keep the battery charged.

Figure 19. In recreational vehicles, a wind turbine can be used to supply electricity to dc powered devices and keep the battery charged. The recreational vehicle pictured above also uses a solar panel to produce electricity.

Effect of using energy-efficient electric equipment on the size and cost of stand-alone wind power systems for dc loads

The daily energy demand (expressed in Wh / day or kWh / day) of each of the various loads that a stand-alone wind power system has to supply must be considered to establish the total daily energy demand that is expected. The daily energy demand of a load is established by multiplying the power rating (expressed in W or kW) of the load by the time (expressed in hours) the load is expected to be used every day. The higher the total daily energy demand that is expected, the larger the size (in terms of either rated power or current capacity) of the wind turbine, electronic devices (e.g., the charge controller), and battery required in the stand-alone wind power system to ensure that the demand is met. This has a direct impact on the cost of the stand-alone wind power system since the cost of each of these components increases with size. Consequently, reducing the total daily energy demand is highly desirable because it reduces the size, and thus the cost, of the stand-alone wind power system required in any application.

Reduction in the total daily energy demand can be done by reducing the time of use of the loads. However, this alternative is limited, and sometimes, it is simply not applicable. Reduction in the total daily energy demand can also be achieved by using electric equipment that is energy efficient, i.e., loads that require less power to perform the same task. For instance, using LED lamps instead of conventional incandescent lamps for lighting is a good means of reducing the total daily energy demand, and thus, the size of a stand-alone wind power system for dc loads. This is due to the fact that an LED lamp generally uses about 5 to 7 times less energy than a conventional incandescent lamp to produce an equivalent amount of light.

For example, let's consider a cabin where two 60 W incandescent lamps are judged sufficient for lighting. Considering that the lamps are lit 4 hours a day, this results in a daily energy demand of 480 Wh. On the other hand, using LED lamps that are assumed to consume 5 times less energy than the incandescent lamps results in a daily energy demand of 96 Wh, a substantial reduction of 384 Wh in the total daily energy demand. Over a complete year, this represents a reduction in the total energy demand of about 140 kWh.

Figure 20. LED lamps use about 5 to 7 times less energy than conventional incandescent lamps to produce an equivalent amount of light.

Procedure Outline

The Procedure is divided into the following sections:

- Set up and connections
- Main components of a stand-alone wind power system for dc loads
- Adjusting the VR setpoint of the charge controller
- Emulated wind turbine settings
- Setting up a stand-alone wind power system for dc loads
- Stand-alone wind power system operation
  Wind turbine producing no electricity. Wind turbine producing electricity at a rate below the power demand of the dc loads. Wind turbine producing electricity at a rate equal to the power demand of the dc loads. Wind turbine producing electricity at a rate exceeding the power demand of the dc loads.
- Battery charging
- Comparing the energy consumption of two different types of dc lamps

Procedure

⚠ WARNING

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

Set up and connections

In this section, you will set up and connect the equipment required to perform the exercise.

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

   Install the 4 Quadrant Dynamometer Motor and the Wind Turbine Generator and Controller side by side on the work surface, with the 4 Quadrant Dynamometer Motor on the left-hand side of the Wind Turbine Generator and Controller.

   Install the remaining of the equipment required in the workstation.

   To ensure optimal accuracy of torque measurements performed with the equipment, make sure that the code (usually a single letter) on the identification (ID) label affixed to the 4 Quadrant Dynamometer Motor is the same as the code on the motor identification (Motor ID) label affixed to the 4 Quadrant Power Supply and Dynamometer Controller.

   Connect the cable on the 4 Quadrant Dynamometer Motor to the corresponding connector on the 4 Quadrant Power Supply and Dynamometer Controller.

   You will use this equipment later in the exercise to set up a stand-alone wind power system for dc loads.

   Before continuing this exercise, measure the open-circuit voltage of the 48V Lead-Acid Battery Pack. If the open-circuit voltage is lower than 51.2 V, ask your instructor for assistance as the 48V Lead-Acid Battery Pack is probably not fully charged. Appendix C of this course indicates how to fully charge the 48V Lead-Acid Battery Pack before a lab period.

2. Make the connections required to earth the equipment properly.

   If necessary, check with the instructor to ensure that the connections you made provide proper earthing of the equipment.

⚠ WARNING

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

3. Mechanically couple the Wind Turbine Generator and Controller to the 4 Quadrant Dynamometer Motor using the timing belt, then install the protective guard.

   If necessary, check with the instructor to ensure that the machines, the timing belt, and the protective guard are properly installed.

4. Make sure that the main power switch of the 4 Quadrant Power Supply and Dynamometer Controller is set to the O (off) position, then connect its *Power Input* to an ac power outlet that is properly protected.

Make sure that the main power switch of the AC 24V Power Supply is set to the *O* (off) position then connect its *Power Input* to an ac power outlet that is properly protected.

If necessary, check with the instructor to ensure that the ac power outlets to which you connect the equipment are properly protected.

5. Connect the *Power Input* of the Data Acquisition and Control Interface to the *Power Output* of the AC 24V Power Supply.

   Connect the *Auxiliary Power Input* of the Wind Turbine Generator and Controller to the *Power Output* of the AC 24V Power Supply.

6. Ask your instructor to turn on (i.e., to unlock) electric power at your workstation, if applicable.

7. Turn the AC 24V Power Supply on.

8. Turn the 4 Quadrant Power Supply and Dynamometer Controller on, then set the *Operating Mode* switch to *Power Supply*.

9. 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 4 Quadrant Power Supply and Dynamometer Controller to a USB port of the host computer.

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

    In LVDAC-EMS, make sure that the Data Acquisition and Control Interface and the 4 Quadrant Power Supply and Dynamometer Controller are detected. Make sure that the *Computer-Based Instrumentation (two phases)* function for the Data Acquisition and Control Interface is available. Also make sure that the *Turbine Emulator* function for the 4 Quadrant Power Supply and Dynamometer Controller is available. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network.

Main components of a stand-alone wind power system for dc loads

In this section, you will gather the key specifications of the 48V Lead-Acid Battery Pack, Wind Turbine Generator and Controller, and DC 48V Lamps module. You will then use these specifications to verify that these pieces of equipment can work together without causing problems.

11. Observe the 48V Lead-Acid Battery Pack. Notice that it consists of four batteries connected in series. The nominal voltage of each battery is 12 V.

    In the remaining of this exercise, the 48V Lead-Acid Battery Pack is also referred to as the battery.

What are the battery voltage and battery capacity indicated on the front panel of the 48V Lead-Acid Battery Pack?

Battery voltage: ______ V

Battery capacity: ______ Ah

Battery voltage: 48 V

Battery capacity: 9 Ah

12. Observe the Wind Turbine Generator and Controller. This module mainly consists of a wind turbine generator with built in rectifier and charge controller. Notice that a control knob (*Max. Charge Voltage* knob) on the module allows the VR setpoint of the charge controller to be adjusted.

The charge controller (-T1) in the Wind Turbine Generator and Controller includes a three-phase rectifier. This allows the charge controller to be connected to the wind turbine generator windings (-G1) directly. An external diode rectifier (-T2) is also provided in the Wind Turbine Generator and Controller to convert ac power produced by the wind turbine generator into dc power without using the built-in charge controller.

Record the range of voltage values to which the VR setpoint of the charge controller (*-T1*) can be adjusted, in the space below.

VR setpoint range: ______ V to ______ V

VR setpoint range: 51 V to 69 V

Does the VR setpoint range match the battery voltage? Explain briefly.

Yes. The VR setpoint required to charge a 48 V lead-acid battery is between 56 V and 58 V. This is within the VR setpoint range (51 V to 69 V) of the charge controller in the Wind Turbine Generator and Controller.

13. Observe the DC 48V Lamps module. The voltage rating of the incandescent lamp and the LED lamp in the DC 48V Lamps module is 48 V. Are these lamps compatible with the battery (system) voltage?

❑ Yes ❑ No

Yes

Adjusting the VR setpoint of the charge controller

In this section, you will adjust the VR setpoint (i.e., the maximum charge voltage) of the charge controller in the Wind Turbine Generator and Controller to the value required to charge the 48V Lead-Acid Battery Pack.

14. On the Wind Turbine Generator and Controller, set the *Charge/Stop* switch to the *Charge* position, then turn the *Max. Charge Voltage* knob fully counterclockwise.

15. In LVDAC-EMS, do the settings required to make the 4 Quadrant Power Supply and Dynamometer Controller operate as a variable-voltage dc source. Set the dc source voltage to 57.6 V. This corresponds to the value of maximum charge voltage commonly used with 48 V lead-acid battery packs.

The output terminals (*1* and *N*) of the power supply in the 4 Quadrant Power Supply and Dynamometer Controller are the terminals of the variable-voltage dc source.

In LVDAC-EMS, enable continuous refresh of the meters (dc voltmeter and ammeter, power meter, and energy meter) on the variable-voltage dc source.

At the moment, leave the variable-voltage dc source off.

16. Connect terminals *1* and *N* of the power supply in the 4 Quadrant Power Supply and Dynamometer Controller to the positive (+) and negative (-) output terminals of the charge controller (*-T1*) in the Wind Turbine Generator and Controller, respectively.

In LVDAC-EMS, turn the variable-voltage dc source on. This applies a dc voltage of 57.6 V to the output of the charge controller in the Wind Turbine Generator and Controller.

17. On the Wind Turbine Generator and Controller, slowly turn the *Max. Charge Voltage* control knob in the clockwise direction until the *Status* LED on the charge controller starts to blink. This sets the VR setpoint of the charge controller to the value of the source voltage (i.e., 57.6 V).

In LVDAC-EMS, turn the variable-voltage dc source off.

Disconnect terminals *1* and *N* of the power supply in the 4 Quadrant Power Supply and Dynamometer Controller from the positive (+) and negative (-) output terminals of the charge controller in the Wind Turbine Generator and Controller.

Emulated wind turbine settings

In this section, you will make the settings required to make the 4 Quadrant Power Supply and Dynamometer Controller and the 4 Quadrant Dynamometer Motor operate as a wind turbine emulator.

18. On the 4 Quadrant Power Supply and Dynamometer Controller, set the *Operating Mode* switch to *Dynamometer*. This setting allows the 4 Quadrant Power Supply and Dynamometer Controller and the 4 Quadrant Dynamometer Motor to operate as a prime mover, a brake, or both, depending on the selected function.

19. In LVDAC-EMS, do the settings required to make the 4 Quadrant Power Supply and Dynamometer Controller and the 4 Quadrant Dynamometer Motor operate as a wind turbine emulator, i.e., a prime mover emulating wind blowing onto the blades mounted at the end of a wind turbine rotor. Then, set the wind turbine emulator as follows:

- Wind turbine type: 1.15 m diameter, 3 blade rotor
- Wind speed control: manual (slider)
- Wind speed: 4.2 m/s

The settings above make the 4 Quadrant Power Supply and Dynamometer Controller and the 4 Quadrant Dynamometer Motor emulate a wind turbine having a 1.15 m diameter, 3 blade rotor. In other words, this emulates the torque-speed characteristic at the rotor of the wind turbine, but without the need for wind and rotor blades.

At the moment, do not start the wind turbine emulator. The emulated wind turbine will be used in the next section of the exercise to implement a stand-alone wind power system for dc loads.

Setting up a stand-alone wind power system for dc loads

In this section, you will set up a stand-alone wind power system for dc loads using the Data Acquisition and Control Interface, emulated wind turbine, Wind Turbine Generator and Controller, 48V Lead-Acid Battery Pack, and DC 48V Lamps module.

20. On the 48V Lead-Acid Battery Pack, make sure that the circuit breaker is open (lever set to the *O* (off) position).

On the DC 48V Lamps module, make sure that the lamp switches are set to the *O* (off) position.

21. Use the Data Acquisition and Control Interface, emulated wind turbine, Wind Turbine Generator and Controller, 48V Lead-Acid Battery Pack, and DC 48V Lamps module to set up the stand-alone wind power system for dc loads shown in the diagram of Figure 21. This system uses a wind turbine with built-in rectifier and charge controller (these components are in the Wind Turbine Generator and Controller module) like the stand-alone wind power system for dc loads shown in Figure 4 of the discussion. The dc loads connected to the system consist of the incandescent lamp and the LED lamp in the DC 48V Lamps module.

To minimize the amount of equipment required to perform the exercise, the stand-alone wind power system in Figure 21 has no load controller to prevent battery overdischarge.

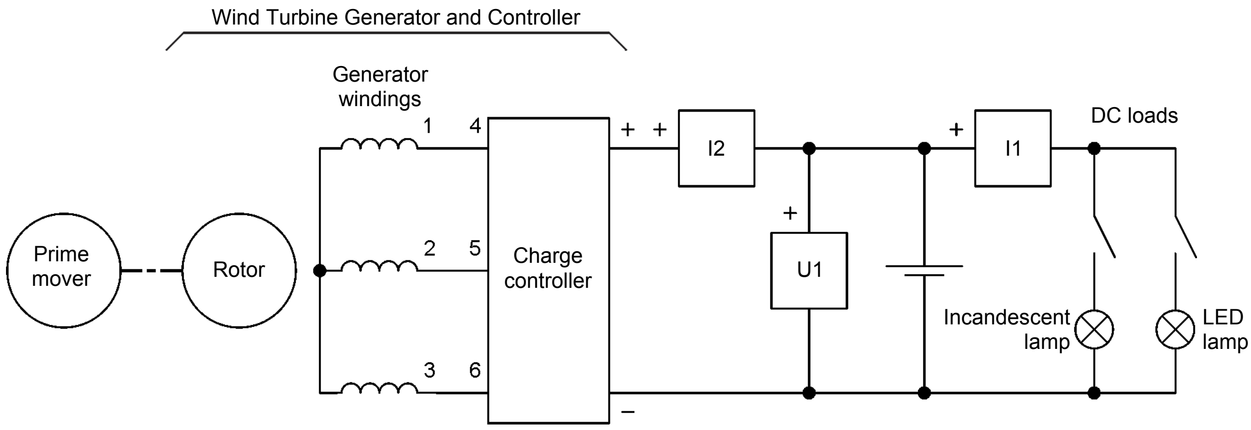


Figure 21. Stand-alone wind power system for dc loads.

22. In LVDAC-EMS, set meters to measure the following parameters:

- Average (dc) value of the battery (system) voltage (input *U1*)
- Average (dc) value of the charge controller output current (input *I2*)
- Average (dc) value of the load current (input *I1*)

These meters will be used throughout the exercise to monitor the operation of the stand-alone wind power system for dc loads.

Make sure that continuous refresh of the meters in LVDAC-EMS is enabled.

Stand-alone wind power system operation

In this section, you will observe the operation of the stand-alone wind power system for dc loads at various wind speeds.

Wind turbine producing no electricity

23. On the 48V Lead-Acid Battery Pack, close the circuit breaker by setting its lever to the *I* (on) position.

On the DC 48V Lamps module, turn the incandescent and LED lamps on.

Record the values of the battery (system) voltage, charge controller output current, and load current indicated by the meters set in in LVDAC-EMS.

Battery voltage ($U_{Batt.}$): ______ V

Charge controller output current ($I_{Controller.}$): ______ A

Battery current ($I_{Batt.}$): ______ A

Load current (I_{Load}): ______ A

Battery voltage ($U_{Batt.}$): 49.8 V

Charge controller output current ($I_{Controller.}$): -0.01 A

Battery current ($I_{Batt.}$): 1.33 A

Load current (I_{Load}): 1.32 A

24. On the 48V Lead-Acid Battery Pack, open the circuit breaker by setting its lever to the *O* (off) position. The incandescent and LED lamps should go out.

Modify the equipment connection so that current input *I1* of the Data Acquisition and Control Interface is in series with the battery, as shown in Figure 22. This allows the battery current to be measured using current input *I1* of the Data Acquisition and Control Interface.

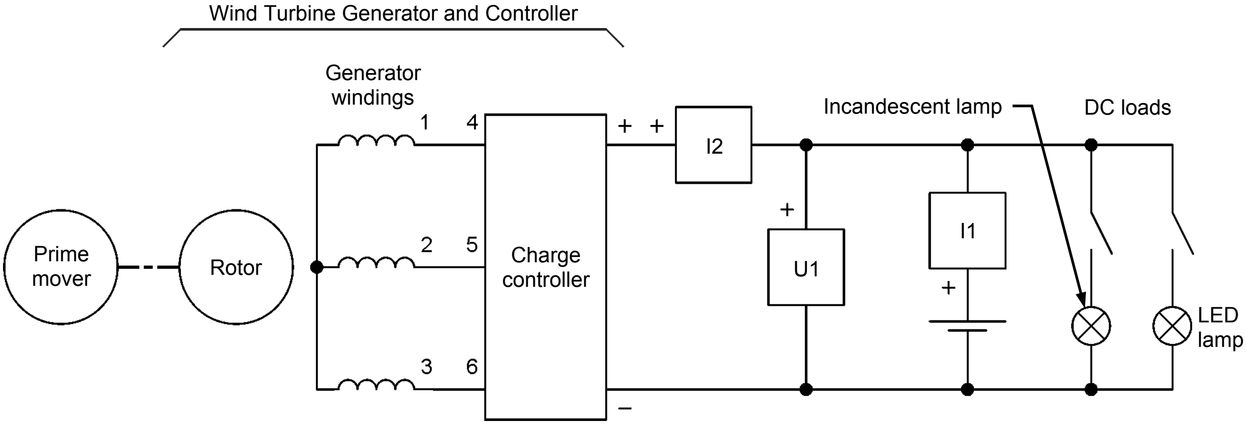


Figure 22. Stand-alone wind power system for dc loads.

25. On the 48V Lead-Acid Battery Pack, close the circuit breaker by setting its lever to the *I* (on) position. The incandescent and LED lamps should light up.

Record the value of the battery current indicated in LVDAC-EMS, in the space provided in step 23.

Do the values of the charge controller output current, battery current, and load current indicate that the battery provides all of the load current? Explain briefly.

Yes. With the polarity of the ammeters (current inputs of the Data Acquisition and Control Interface) shown in the diagrams of Figure 21 and Figure 22, the following equation relates the load current (I_{Load}) to the charge controller output current ($I_{Controller}$) and battery current ($I_{Batt.}$): $I_{Load} = I_{Controller} + I_{Batt.}$. Consequently, I_{Load} equals $I_{Batt.}$ when $I_{Controller}$ is 0 A.

What is the polarity of the battery current? What does this indicate?

The polarity of the battery current is positive thereby indicating that current exits the positive terminal of the battery. In other words, this indicates that the battery is discharging.

Let the system operate until the battery voltage decreases to 49.5 V. This should take about 10 minutes when the 48V Lead-Acid Battery Pack is fully charged, as requested at the beginning of the exercise.

Wind turbine producing electricity at a rate below the power demand of the dc loads

26. In LVDAC-EMS, start the wind turbine emulator. Make sure that continuous refresh of the meters (speed, torque, power, and energy meters) on the wind turbine emulator is enabled.

Observe that the wind turbine generator in the Wind Turbine Generator and Controller begins to rotate. Notice that the wind turbine generator begins to produce electricity since the charge controller now supplies some current.

27. In LVDAC-EMS, slowly increase the wind speed of the wind turbine emulator up to 5.5 m/s while observing the values of the charge controller output current and battery current indicated by the meters set in LVDAC-EMS. Notice that the value of the battery current decreases as that of the charge controller output current increases. Also notice that the value of the battery (system) voltage varies little when the wind speed changes. Consequently, the load current remains virtually unchanged when the wind speed changes.

In LVDAC-EMS, adjust the wind speed of the wind turbine emulator so that the values of the charge controller output current and battery current indicated by the meters set in LVDAC-EMS are approximately equal.

Record the values of the battery (system) voltage, charge controller output current, and battery current indicated by the meters set in LVDAC-EMS.

Copy the value of the load current that you recorded in step 23, in the space below.

Battery voltage ($U_{Batt.}$): ______ V

Charge controller output current ($I_{Controller.}$): ______ A

Battery current ($I_{Batt.}$): ______ A

Load current (I_{Load}): ______ A

Battery voltage ($U_{Batt.}$): 49.8 V

Charge controller output current ($I_{Controller.}$): 0.64 A

Battery current ($I_{Batt.}$): 0.68 A

Load current (I_{Load}): 1.32 A

Do the values of the charge controller output current, battery current, and load current indicate that the charge controller and the battery each provide about half of the load current? Explain briefly.

Yes. $I_{Controller}$ equals $I_{Batt.}$, and thus, $I_{Load} = I_{Controller} + I_{Batt.} = 2I_{Controller} = 2I_{Batt.}$. Consequently, $I_{Controller}$ equals $I_{Load}/2$ and $I_{Batt.}$ equals $I_{Load}/2$.

Wind turbine producing electricity at a rate equal to the power demand of the dc loads

28. In LVDAC-EMS, increase the wind speed of the wind turbine emulator until the value of the battery current indicated in LVDAC-EMS is approximately zero.

Record the values of the battery (system) voltage, charge controller output current, and battery current indicated by the meters set in LVDAC-EMS.

Copy the value of the load current that you recorded in step 23, in the space below.

Battery voltage ($U_{Batt.}$): ______ V

Charge controller output current ($I_{Controller.}$): ______ A

Battery current ($I_{Batt.}$): _______ A

Load current (I_{Load}): _______ A

Battery voltage ($U_{Batt.}$): 50.6 V

Charge controller output current ($I_{Controller.}$): 1.32 A

Battery current ($I_{Batt.}$): 0.00 A

Load current (I_{Load}): 1.32 A

Do the values of the charge controller output current, battery current, and load current indicate that the charge controller provides all of the load current? Explain briefly.

Yes. $I_{Load} = I_{Controller} + I_{Batt.}$. Consequently, I_{Load} equals $I_{Controller}$ when $I_{Batt.}$ is 0 A.

Wind turbine producing electricity at a rate exceeding the power demand of the dc loads

29. In LVDAC-EMS, slightly increase the wind speed of the wind turbine emulator so that the battery current indicated in LVDAC-EMS is about -0.2 A. What does the negative polarity of the battery current indicate?

The negative polarity of the battery current indicates that current enters the positive terminal of the battery. In other words, this means that the battery is charging.

In LVDAC-EMS, slowly increase the wind speed of the wind turbine emulator until the battery current indicated in LVDAC-EMS is about -0.5 A.

Record the values of the battery (system) voltage, charge controller output current, and battery current indicated by the meters set in LVDAC-EMS.

Copy the value of the load current that you recorded in step 23, in the space below.

Battery voltage ($U_{Batt.}$): _______ V

Charge controller output current ($I_{Controller.}$): _______ A

Battery current ($I_{Batt.}$): _______ A

Load current (I_{Load}): _______ A

Battery voltage ($U_{Batt.}$): 51.9 V

Charge controller output current ($I_{Controller.}$): 1.83 A

Battery current ($I_{Batt.}$): -0.51 A

Load current (I_{Load}): 1.32 A

In LVDAC-EMS, stop the wind turbine emulator. Observe that the wind turbine generator in the Wind Turbine Generator and Controller stops rotating and the current at the charge controller output decreases to zero. This interrupts battery charging while you answer the questions in the next procedure step.

30. Do the values of the charge controller output current, battery current, and load current recorded in the previous step indicate that the charge controller supplies all of the load current as well as the current charging the battery? Explain briefly.

Yes. $I_{Load} = I_{Controller} + I_{Batt.}$. Consequently, $I_{Controller} = I_{Load} - I_{Batt.}$. Since $I_{Batt.}$ is of negative polarity, it adds to I_{Load}.

Compare the various values of the battery voltage recorded so far. Does the battery voltage, which is also the load voltage, vary slightly depending on whether the battery is charging or discharging?

Yes, the battery voltage (load voltage) measured when the battery is charging (about 52 V) is a little higher than the voltage measured when the battery is discharging (less than 50 V).

In LVDAC-EMS, start the wind turbine emulator. Battery charging resumes and, a little after, the values of the battery voltage, charge controller output current, battery current, and load current should be similar to those recorded in step 29.

31. On the DC 48V Lamps module, turn the incandescent and LED lamps off.

Record the values of the battery (system) voltage, charge controller output current, and battery current indicated by the meters set in LVDAC-EMS.

Battery voltage ($U_{Batt.}$): _______ V

Charge controller output current ($I_{Controller.}$): _______ A

Battery current ($I_{Batt.}$): _______ A

Load current (I_{Load}): 0.00 A

Battery voltage ($U_{Batt.}$): 54.0 V

Charge controller output current ($I_{Controller.}$): 1.72 A

Battery current ($I_{Batt.}$): -1.72 A

Load current (I_{Load}): 0.00 A

In LVDAC-EMS, stop the wind turbine emulator in order to interrupt battery charging while you perform the remaining of this procedure step.

Observe that the charge controller output current and battery current recorded above have the same value but are of opposite polarity. This indicates that all of the charge controller output current is used to charge the battery. This is normal because the two lamps are off (no load current).

Compare the values of the charge controller output current recorded in this step (both lamps off) and in step 29 (both lamps on). Are they about the same? Explain briefly.

Yes. This is because the MPP tracking algorithm in the charge controller maintains the amount of electric power which the wind turbine generator produces to the maximum value possible for the present wind speed. Consequently, the charge controller output current is about the same with or without dc loads connected to the system.

In fact, the charge controller output current decreases slightly when the dc loads are disconnected from the system. This is because disconnecting the dc loads from the system increases the battery charging current significantly, and thus, the battery voltage increases slightly. Consequently, the charge controller has to provide slightly less current to provide the same amount of power.

Battery charging

In this section, you will observe the operation of the charge controller when the battery is charging.

32. In LVDAC-EMS, start the wind turbine emulator. Battery charging resumes and, a little after, the values of the battery voltage, charge controller output current, battery current, and load current should be similar to those recorded in step 31.

Observe that the battery voltage increases slowly as the battery is charging. Let the system operate until the battery voltage reaches the VR setpoint (57.6 V). This should take about 5 to 10 minutes.

The battery voltage may momentarily exceed the VR setpoint because the charge controller does not react instantly to variations in the battery voltage.

Describe what happens when the battery voltage reaches the VR setpoint.

Battery charging control continues after the battery voltage reached the VR setpoint. Continue to observe the battery voltage and the system operation while answering the present question. This should allow you to make observations that are useful for the next procedure step.

When the battery voltage reaches the VR setpoint, the charge controller short-circuits the wind turbine generator output. This causes the electrical load applied to the wind turbine generator to increase markedly, thereby producing a strong braking torque at the wind turbine rotor and a sharp decrease in the rotor speed. This greatly reduces the amount of power the wind turbine generator produces, and consequently, stops battery charging.

33. Observe that the battery voltage decreases slowly when battery charging is interrupted. Let the system operate until the battery voltage reaches the VRR setpoint (about 52 V). This generally takes less than 2 minutes.

Describe what happens when the battery voltage reaches the VRR setpoint.

When the battery voltage reaches the VRR setpoint, the charge controller stops short-circuiting the wind turbine generator output. This eliminates the strong braking torque produced in the wind turbine. Consequently, the wind turbine starts rotating and producing electricity, and battery charging resumes.

34. In LVDAC-EMS, stop the wind turbine emulator. This stops battery charging.

Comparing the energy consumption of two different types of dc lamps

In this section, you will compare the energy consumption of two dc lamps of different types (incandescent and LED) which produce approximately the same amount of light.

35. In LVDAC-EMS, set a meter to measure power at the dc loads from the battery voltage and current (voltage input *U1* and current input *I1*).

The load current is equal to the battery current because the charge controller output current is null.

On the DC 48V Lamps module, turn the incandescent lamp on.

Record the battery (incandescent lamp) voltage, current, and power indicated by the meters set in LVDAC-EMS.

Battery (incandescent lamp) voltage: ______ V

Battery (incandescent lamp) current: ______ A

Battery (incandescent lamp) power: ______ W

Battery (incandescent lamp) voltage: 50.8 V

Battery (incandescent lamp) current: 1.17 A

Battery (incandescent lamp) power: 59.4 W

Use the lamp power you just measured to calculate the daily energy demand of the incandescent lamp. Base your calculation on 4 hours of use per day.

Daily energy demand of the incandescent lamp: 59.4 W x 4 h = 237.6 Wh

36. Notice the amount of light which the incandescent lamp produces. On the DC 48V Lamps module, turn the incandescent lamp off then turn the LED lamp on. Do the two lamps produce approximately the same amount of light?

❑ Yes ❑ No

Yes

Record the battery (LED lamp) voltage, current, and power indicated by the meters set in LVDAC-EMS.

Battery (LED lamp) voltage: ______ V

Battery (LED lamp) current: ______ A

Battery (LED lamp) power: ______ W

Battery (LED lamp) voltage: 51.4 V

Battery (LED lamp) current: 0.19 A

Battery (LED lamp) power: 9.8 W

Use the lamp power you just measured to calculate the daily energy demand of the LED lamp. Base your calculation on 4 hours of use per day.

Daily energy demand of the LED lamp: 9.8 W x 4 h = 39.2 Wh

On the DC 48V Lamps module, turn the LED lamp off.

37. Compare the daily energy demand of the LED lamp with that of the incandescent lamp.

The daily energy demand of the LED lamp (39.2 Wh) is 6.06 times less than that of the incandescent lamp (237.6 Wh).

Does this confirm that the LED lamp is more efficient than the incandescent lamp at converting electricity into light? Explain briefly.

Yes. The LED lamp produces approximately the same amount of light as the incandescent lamp while consuming about 6 times less energy than the incandescent lamp.

38. Close LVDAC-EMS.

Turn the 4 Quadrant Power Supply and Dynamometer Controller off.

Turn the AC 24V Power Supply off.

Turn electric power off at your workstation, if applicable.

Remove all circuit connections, finishing with the equipment earthing connections.

Remove the protective guard. Remove the timing belt that mechanically couples the 4 Quadrant Dynamometer Motor to the Wind Turbine Generator and Controller.

Return all equipment to its storage location.

CONCLUSION

In this exercise, you became familiar with the configuration and operation of stand-alone wind power systems for dc loads. You learned how to use the specifications of the charge controller, battery, and load controller selected for a specific stand-alone wind power system to verify that they can work together without causing problems. You saw how the charge controller performs battery charging control and keeps the wind turbine generator loaded at all times to prevent rotation at excessive speed. You also saw how the load controller prevents battery overdischarge. You learned that choosing energy efficient electric equipment (e.g., using LED lamps instead of incandescent lamps) is a means of reducing the size and cost of the stand-alone wind power system for dc loads required in any application. You discovered several common applications of stand-alone wind power systems for dc loads.

Review Questions

1. What are the main functions of the charge controller in a stand-alone wind power system? Assume that the charge controller is built in the wind turbine.

   The charge controller in a stand-alone wind power system, when built in the wind turbine, controls battery charging, makes the wind turbine operate at the maximum power point (MPP), and keeps the wind turbine generator loaded at all times to prevent rotation at excessive speeds.

2. Briefly describe the function of the load controller in a stand-alone wind power system for dc loads.

   The load controller prevents overdischarge of the battery by disconnecting the load when the battery voltage decreases down to a certain value, called the low-voltage disconnect (LVD) setpoint. The controller automatically reconnects the load when the battery voltage increases up to a certain value, called the low-voltage reconnect (LVR) setpoint.

3. Name two common applications of stand-alone wind power systems for dc loads.

   Common applications of stand-alone wind power systems for dc loads: electric power provision in small buildings, electric power provision in small boats, battery charging in recreational vehicles.

4. The battery bank in a stand-alone wind power system consists of three battery strings connected in parallel, each battery string consisting of two batteries connected in series. The voltage and capacity of each battery are 12 V and 75 Ah, respectively. What are the system voltage and the system capacity (i.e., the capacity of the battery bank)?

   Each battery string consists of two 12 V batteries connected in series. The system voltage is thus 24 V (2 x 12 V). The capacity of each of the three battery strings is 75 Ah. The system capacity is thus 225 Ah (3 x 75 Ah).

5. What is the effect of using energy-efficient electric equipment on the size and cost of a stand-alone wind power system for dc loads? Explain briefly.

   Using electric equipment that is energy efficient, i.e., loads that require less power to perform the same task, reduces the daily energy demand. Reducing the energy demand allows the size, and thus the cost, of the stand-alone wind power system required in any application to be reduced.

Bibliography

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