N3

Electrical Trade Theory

Student Book

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Contents

Module 10 Renewable energy

What is covered?

In this module, you will learn more about solar energy as a form of renewable energy and how direct current is converted into alternating current.

Learning outcomes

After studying this module, you should be able to:

Unit 1

- State the advantages and disadvantages of solar energy.
- Explain how solar energy is converted into electrical energy.
- Explain how direct current is converted into alternating current.

Unit 2

- Explain what an uninterrupted power supply (UPS) is.
- Explain the purpose of a UPS.

Unit 1: Solar energy

LEARNING OUTCOMES

- State the advantages and disadvantages of solar energy.
- Explain how solar energy is converted into electrical energy.
- Explain how direct current is converted into alternating current.

Introduction

Approximately 80% of the world's energy consumption is derived from fossil fuels, such as coal, oil and natural gas. These fuel sources are the result of the natural decaying process of organisms over millions of years. Approximately 71% of the electrical energy South Africa currently use is derived from coal.

The use of fossil fuels is of environmental concern. They increase the level of pollutants in the atmosphere, and are major emitters of carbon dioxide (CO2) and other greenhouse gases. Greenhouse gases affect climate change and result in extreme climatic conditions, such as flooding, fires and drought. In addition, fossil fuels are unsustainable energy sources, as there is a limited supply on Earth.

These factors resulted in an increase in the use of renewable sources in the overall energy mix of many countries. Renewable energy is derived from sources that are replenishable within our timescale. Renewable energy includes wind, solar PV (photo-voltaic), concentrated solar power (CSP), solar thermal, geothermal, hydro, wave and tidal energy.

By 2030, South Africa proposes to have 34% of its electrical energy mix derived from renewable sources. The current contribution of renewable energy to the electrical energy mix is 7%.

Solar energy

Solar energy is the radiant energy derived from the Sun. In South Africa, the average solar radiation levels range from 4,5 to 6,5 kWh/m2. The average daily household energy consumption in South Africa is approximately 30 kWh.

There are a number of ways in which this radiant energy can be converted into electricity or other forms of energy, which will be discussed later. In the following section, we will discuss the advantages and disadvantages of solar energy.

Advantages of solar energy

- Solar energy is a renewable source of energy. It will not be depleted within the human lifespan.
- Solar energy installations do not emit toxic gases during operation.
- In certain markets, solar energy is cheaper than coal.
- Countries are less vulnerable to the fluctuation of energy markets, for example, the price of coal.

- Private solar energy systems require minimal maintenance.
- Solar systems based on photovoltaic technology are easy to upgrade.
- Excess energy can be sold back to the utility (for residential systems, where possible).
- Solar energy offers a relatively low return on investment (ROI) period. Depending on the market, the capital installations costs can be paid off in a relatively short period.
- Residential or private users can look forward to free energy after the completion of the capital outlay period.
- Residential or private users are immune from grid outages as a result of load shedding or grid faults.
- Residential or private users are immune from poor grid power quality.
- Solar energy systems are relatively easy to install – no need for trenching or similar infrastructural requirements (for roof-top installations).
- Roof-top installation is possible in domestic and commercial buildings – no need for additional land.
- If the installation is in compliance with local standards, it is safe for residential or private users.
- Modern developments are aimed at improving overall aesthetics, when used on roof-tops.

Disadvantages of solar energy

- Solar energy systems do not provide energy at night. These have to be coupled with adequately specified storage systems.
- Solar energy systems deliver a reduced energy output in winter and during transitional cloud coverage and have to be coupled with adequately specified storage systems.
- PV-modules have low conversion efficiencies of around 20%. The conversion efficiency is the amount of light energy converted into electricity.
- Non-silicon PV-modules require specialised recycling technologies.
- Solar systems are more expensive in markets where cheap coal is in abundance, such as in South Africa.
- The energy output of PV modules degrades over time (approximately 1% per year).
- Solar panels need to be cleaned regularly as a matter of routine to ensure optimal output.
- CSP plants require a large land area.
- Traditional PV modules can have a negative impact on the aesthetics of a building

Conversion of solar energy into electrical energy

Solar thermal

The simplest conversion of radiant energy to a useful form of energy, is in the heating of water or other fluids. This is known as [solar thermal] and is commonly used to complement the electric hot water geyser in homes or commercial properties.

In this case, the radiant energy heats cold water contained in thin plastic or glass tubes. The heated water is then fed into the electric geyser.

Figure 10.1 Rooftop solar geysers

In the next section, we are going to discuss two other solar energy systems: PV modules and CSP systems.

PV modules

Figure 10.2 Individual cells of a PV module

Solar photovoltaic (PV) is the name given to systems where the radiant energy is directly converted into electrical energy through the use of specially manufactured PV modules.

As a result of environmental concerns, increased research, and economies of scale, the price of PV modules has dropped dramatically. The price of commercially available panels has dropped by 99% over 40 years.

A PV module is made up of many individual PV cells that are connected in series, or a combination of series and parallel, to achieve the overall panel output voltage and current. The cell utilises the photovoltaic effect, where radiant energy is converted into electrical energy through the use of appropriate materials.

Each cell is made up of two types of semiconductor material: a so-called p-type semiconductor made of silicon that is doped (mixed) with boron and an n-type semiconductor made of silicon and doped with phosphorus.

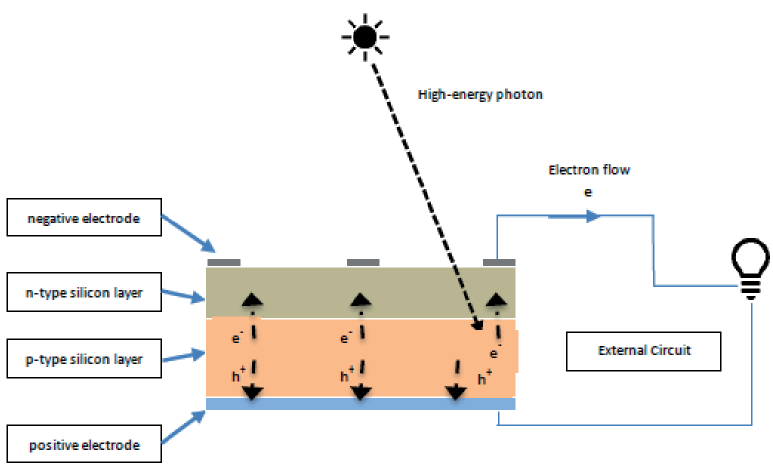

Figure 10.3 Simplified structure of a PV cell

When a high-energy photon from the Sun strikes an electron in the p-type layer, the energy is absorbed by the electron. The electron moves into the conduction band of the material. By virtue of the nature of the materials, the electrons are swept across the interface and into the n-type layer. The vacancy left by the electron in the atom is known as a hole. As electrons fill these holes, the holes can be seen as moving entities (holes are not particles) within the material lattice structure.

If an external circuit and load is attached to the cell, the electrons will flow through the circuit and recombine with the holes on the positive electrode of the cell.

Figure 10.4 A rooftop PV panel

The electrical energy provided by a PV cell (and by implication a PV module) is direct current (DC). If an alternating current (AC) output is required, an inverter and other protective and controlling components would be included in the system.

Commercial PV modules have power capacities ranging from a few watts to 500 W, with open-circuit voltages standardised to 12, 24 and 48 V.

A typical PV-based stand-alone residential system, with battery backup, is shown in Figure 10.5. A stand-alone system is completely isolated from the grid. A changeover switch (either manual or automatically controlled), allows the residential load to be switched to either the grid or the PV system.

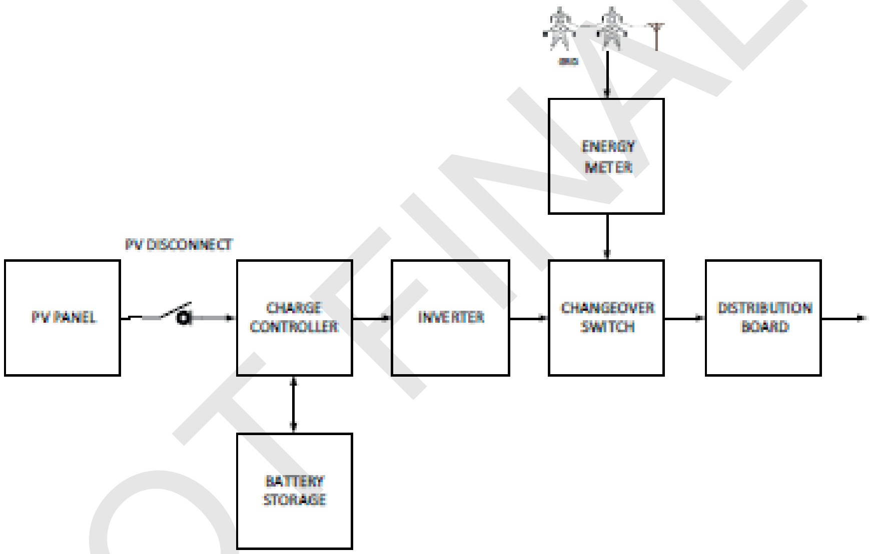

Figure 10.5 Block diagram of a typical residential stand-alone PV system

Most modern systems incorporate most of these functions into one unit – a modern inverter will have the charge controller, inverter, metering, automatic changeover (isolation between PV and grid) and many other monitoring and control functions built into a single unit. The functional blocks provide the following:

- **PV panel:** strings of PV modules that convert solar radiant energy into electrical energy
- **PV disconnect switch:** isolates the PV source from the rest of the system for maintenance, or other purposes
- **Charge controller:** controls the flow of energy between the PV panel, the battery and the inverter, in order to optimise the energy usage.

- **Inverter:** converts DC voltage (12, 24 or 48V) to AC mains voltage (230 V, 50 Hz)
- **Changeover switch:** ensures isolation between PV energy and the grid
- **Energy meter:** measures the overall energy provided by the grid and provides energy payment functionality
- **Distribution board:** this is the electrical protection facility of the residence.

Concentrated solar power

Concentrated solar power (CSP), as the name implies, uses mirrors, lenses or troughs to concentrate the radiant energy onto a focal point, where the resultant heating of a fluid is used to drive a steam turbine to generate electricity, or to heat molten salt for the purposes of energy storage.

The collecting areas of CSP plants are large, resulting in capacities in the order of 50 MW to several hundred megawatts. Figure 10.6 shows a CSP plant in Spain.

Figure 10.6 A CSP plant in Spain

A PV system provides direct conversion of solar energy into electricity, but a CSP system comprises a few intermediate conversion processes to convert the radiation to electricity. The radiant energy is first used to heat a fluid to generate steam. The steam is then used to turn a turbine to produce mechanical energy. The turbine is connected to an electrical generator where the mechanical energy is converted into electrical energy.

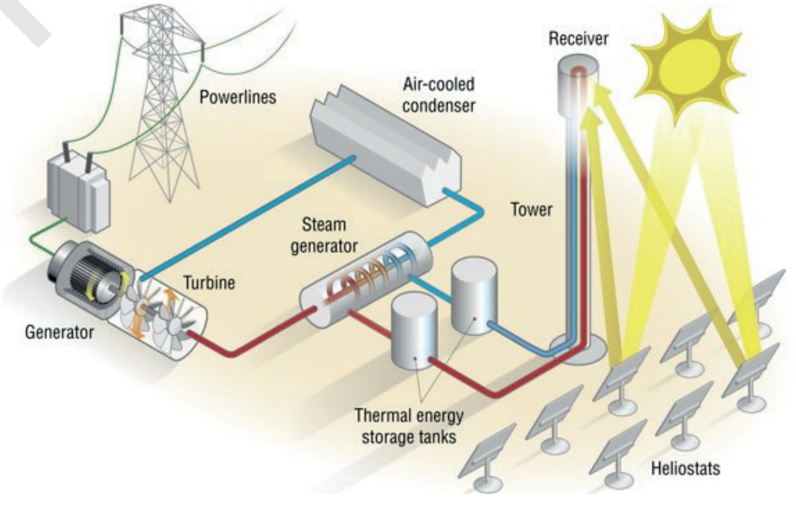

Figure 10.7 Simplified diagram of a CSP plant

The key elements of a CSP system are the following:

- **Heliostats:** these are mirrors, placed across a large area, that focus the radiant energy onto the receiver. The heliostats are mounted on rotating pedestals that track the position of the sun throughout the day.
- **Receiver:** the focal point is situated in a tower and contains a heat exchanger that transfers the heat energy from the focused radiation to a special fluid (molten salt).
- **Thermal energy tanks:** the heated molten salt fluid flows in a circuit that is separated from the rest of the system with storage capability provided in the tanks.
- **Steam generator:** a heat exchanger transfers the heat energy from the molten salt to water, where steam is generated.
- **Turbine/Generator:** steam from the steam generator drives a rotating turbine which, in turn, drives the generator. The generator converts the rotating mechanical energy into electricity and is linked into the grid via the required infrastructure.
- **Air-cooled condenser:** the energy-depleted steam is condensed in an air-cooled condenser and returns to the steam generator heat exchanger. Here, the process is repeated. Note that the water and molten salt circuits are separated.

A CSP plant has the advantage of being able to gather the radiant energy across a large area, so the energy harnessed is relatively large. Another major advantage is that the system provides energy storage through the use of specialised fluids (such as liquid salt), where the heated fluid can be stored in tanks. The plant can therefore continue to convert the energy even after sunset, or under conditions of temporary cloud cover.

How DC is converted into AC

Most household or commercial electrical appliances or products are designed to operate from the AC mains supply (230 V, 50 Hz). However, PV panels provide a DC output, so we use a power inverter, or simply an inverter, DC to AC.

Not only is the inverter required to convert DC to AC, but it also has to increase the magnitude of the voltage from a low value (typically 12 V, 24 V, or 48 V for residential PV systems) to 230 V. The magnitude of the input and output voltages are system dependent and we will be limiting our discussion to residential voltages. However, the general principles employed in the residential inverters are similar to that of commercial inverters. Most commercial inverters employ electronic circuitry to achieve the conversion objectives.

The objective of an inverter is to convert the input DC voltage to a sinusoidal AC output, as shown in Figure 10.8. Note that the peak AC voltage is determined by:

$$V_{\text{sub peak}} = 230 \text{ V} \times \sqrt{2} = 325{,}27 \text{ V}$$

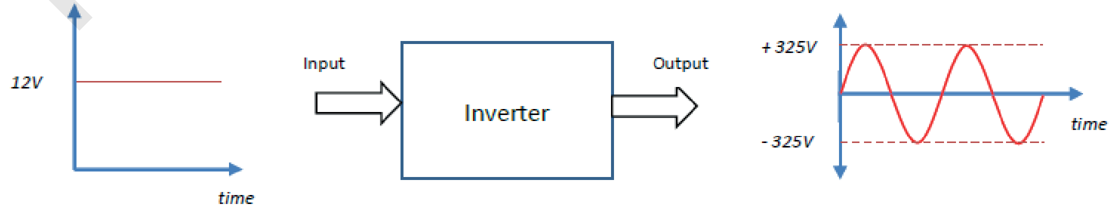

Figure 10.8 A 12 V DC to 230 V AC inverter

Three output types are commonly used to approximate the desired sinusoidal output:

- square wave
- modified sine wave
- near sine wave (pure sine wave).

Square wave output

Square wave output, as shown in Figure 10.9, is simply a square wave having peak values of +230 V and –230 V and a frequency of 50 Hz. Note that the peak and rms value of a square wave is the same. The frequency of the square wave is 50 Hz, since the given period of the wave is 20 ms (f = [1/20 ms] = 50 Hz).

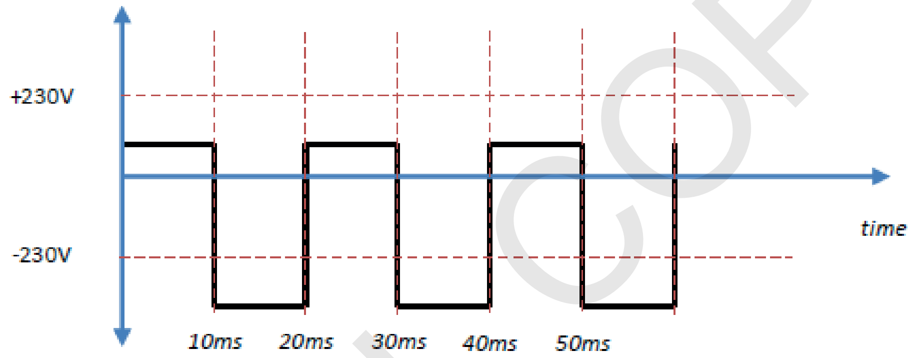

Figure 10.9 The output of a square wave inverter

A square wave output is very easy to generate. Figure 10.10 shows a simplified block diagram of a square wave inverter.

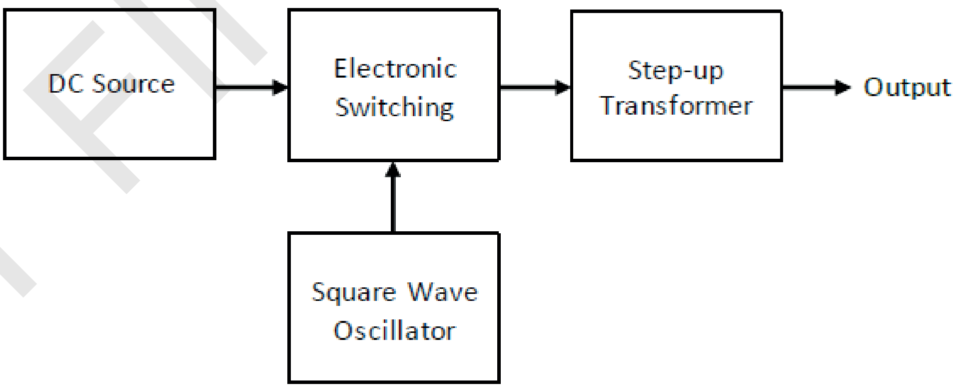

Figure 10.10 Simplified block diagram of a basic inverter

If the inverter is employed in a PV system, the DC source is usually the battery. The square wave oscillator is a low power oscillator that provides the pulses necessary to switch the energy from the DC source through the primary coil of a transformer.

The switching elements employed are dependent on the power and switching requirements, and ranges from power transistors to IGBT (insulated-gate bipolar transistor) devices. The transformer steps up the voltage to the required level suitable for the appropriate mains appliances.

The square wave output is only suitable for appliances that do not employ sensitive electronics (appliances that are essentially resistive). Appliances, such as kettles and heaters, are able to function with a square wave supply. Appliances employing certain types of motors are not recommended to be driven by square wave inverters.

Modified sine wave output

The modified sine wave output is a slight variation of the square wave. The output is shown in Figure 10.11.

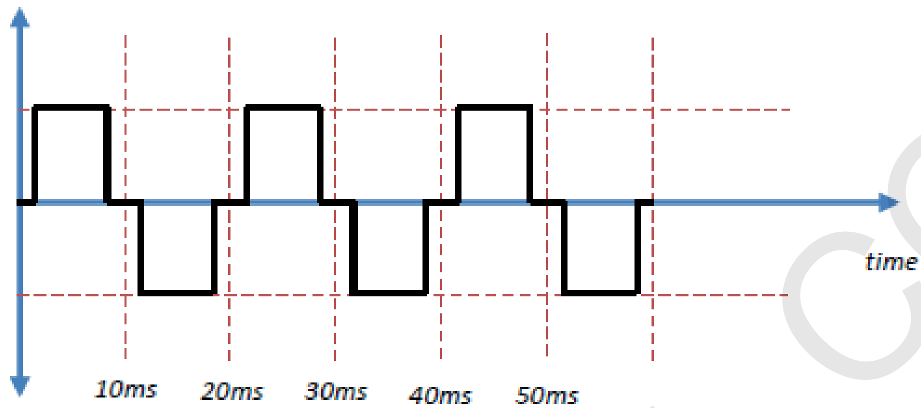

Figure 10.11 Modified sine wave inverter output

Most of the inexpensive commercial inverters provide a modified sine wave output. As with the square wave output, these are suitable when used on appliances that are essentially resistive in nature.

The modified sine wave signal has slightly less harmonic content than the square wave output. Harmonics are high frequency signal components that are present in any periodic, non-sinusoidal signal.

These high frequency signals can be problematic in certain loads, resulting in noise, a decrease in the efficiency of the appliance, or non-functioning if the appliance is particularly sensitivity to harmonics. The square wave and modified sine wave approximations are also respectively known as two-step waveforms (square wave) and three-step waveforms (modified sine).

Near sine wave (pure sine wave) output

Commercial inverters often use the term "pure sine wave" to make the distinction between the two-step square wave and the three-step modified sine wave outputs discussed above. While the term might imply that the output is an exact replica of a sinusoidal signal, the output signal is still an approximation of the ideal sinusoid. This will show in the harmonic content of the output signal: the higher the deviation from the ideal sinusoid, the higher the harmonic content.

A popular technique to generate a near sine wave output is the use of Pulse Width Modulation (PWM). PWM modulates (changes) carrier signals (periodic pulse signal) by another signal (in this case, the desired sinusoidal signal). The modulation is a change in the width of the carrier signal (pulse signal), as a function of the magnitude of the modulating signal (the sinusoidal signal). The signal in Figure 10.12 shows a PWM signal with the original sinusoidal superimposed as a reference. Note that, as the sinusoidal signal increases in magnitude, the width of the pulse increases.

The PWM signal is filtered through a low-pass filter, before being made available to the load. The low-pass filter removes the high-frequency harmonics, leaving a close representation of the original sinusoidal signal. The PWM signal shown in Figure 10.12 is an example of a multistep (five-step) PWM signal.

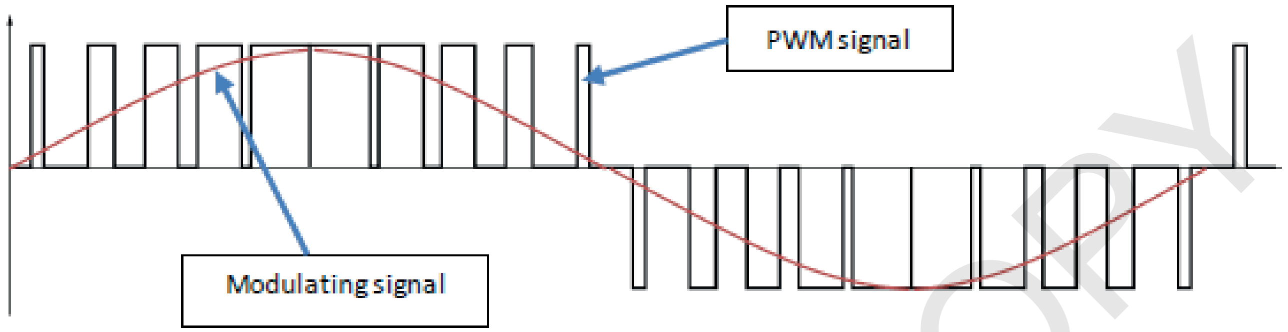

Figure 10.12 PWM signal (five-step) and the sinusoidal signal used to modulate the PWM signal

ACTIVITY 10.1 Energy soures

1. Give two examples of fossil fuels.
2. What fossil fuel is the major source of electrical energy in South Africa?
3. Give two examples of renewable energy sources.
4. What is the major concern regarding the use of fossil fuels?
5. What are the criteria necessary for an energy source to be regarded "renewable"?
6. Give three examples of renewable solar energy systems.
7. List three advantages of solar energy.
8. Indicate whether the following statements are advantages or disadvantages with respect to solar energy.
   a) A PV system works when the sun is shining.
   b) In certain markets, the cost per kWh obtained from PV is less than that obtained from coal.
   c) A PV system without batteries cannot store solar energy.
   d) Commercial PV-systems have efficiencies of around 20%.
   e) A CSP system can provide energy storage.
   f) A PV system requires minimal maintenance.
   g) The capital outlay for a PV system can be recouped in a relatively short period.
   h) The output power of a PV module decreases over time.
9. Describe, using a suitable diagram, how radiant energy is converted into electrical energy in a PV cell.

10. Add labels where indicated in Figure 10.13.

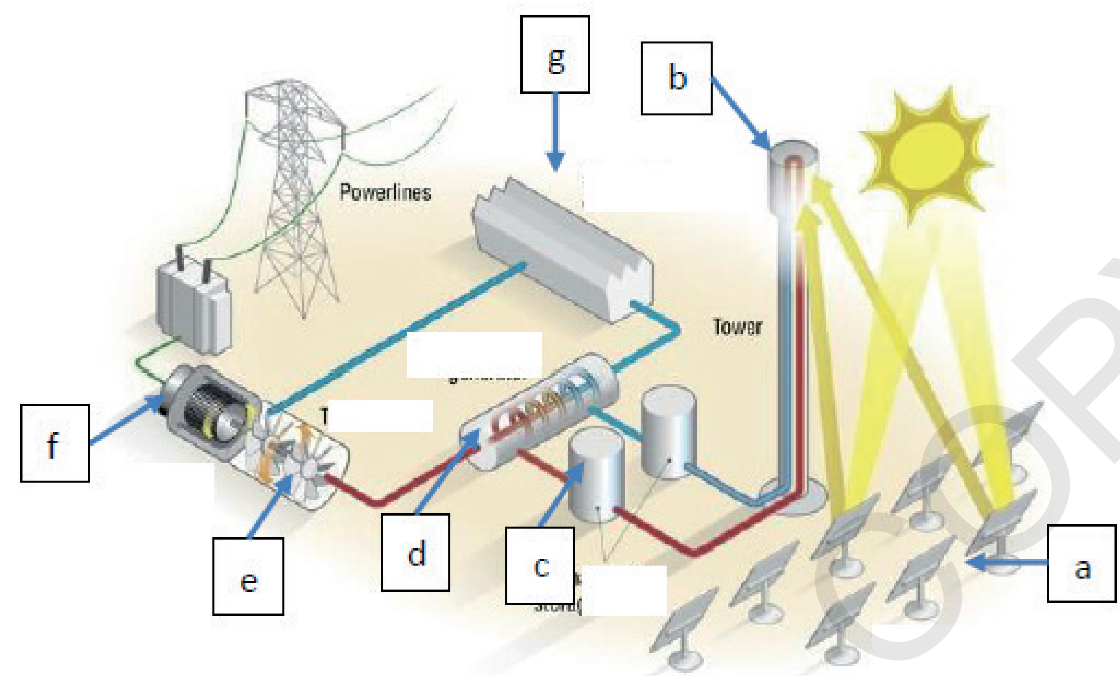

Figure 10.13

11. What is the name of the device used to convert DC to mains level AC?
12. Why will an ordinary electronic oscillator not suffice as an inverter?
13. What is the simplest output that an inverter can provide?
14. What appliances are able to function with a square wave inverter?
15. Draw the output signal of a modified sine wave inverter.
16. Give one advantage of the modified sine wave inverter over the square wave inverter.
17. Draw a simplified block diagram of a modified sine wave inverter.

Unit 2: Uninterrupted power supply

LEARNING OUTCOMES

- Explain what an uninterruptible power supply (UPS) is.
- Explain the purpose of a UPS.

Introduction

In this section, we will discuss the UPS. We look at three different types of UPSs and see how these differ in the way in which the UPS provides a continuation of supply in the event of a mains failure.

The UPS differs from traditional stand-by supplies in the time duration that it responds to a mains outage. A stand-by generator has a response time in the order of minutes, while a UPS has a near instantaneous response to a mains failure.

What is a UPS?

An uninterruptible power supply (UPS) is a device that provides a continuation of supply to a load in the event of a mains failure, or a deviation from the nominal mains supply. A UPS is connected between the grid supply and the load. It comprises an electrical storage component, an inverter and a monitoring/control circuit to ensure functionality of the UPS. The electrical storage element of the UPS is usually provided by a battery (lead-acid, lithium-ion), but other storage systems such as rotating flywheels, super capacitors or hydrogen fuel cells can also be used.

The inverter is used to convert the DC from the battery storage to mains AC. The grid supply ensures that the battery is kept fully charged. Examples of typical UPSs are shown in Figures 10.14 and 10.15. The size of the UPS gives us an indication of the capacity of the UPS (load power) and duration of UPS supply in the event of a loss of incoming supply, since the bulk of the space of the UPS is taken up by the battery. The desktop UPS shown in Figure 10.14 is capable of supplying a 15 W load for a period of approximately two hours.

Figure 10.14 An example of a small, desktop UPS

Figure 10.15 An example of a large UPS used in a data centre

A block diagram of a typical UPS is shown in Figure 10.16.

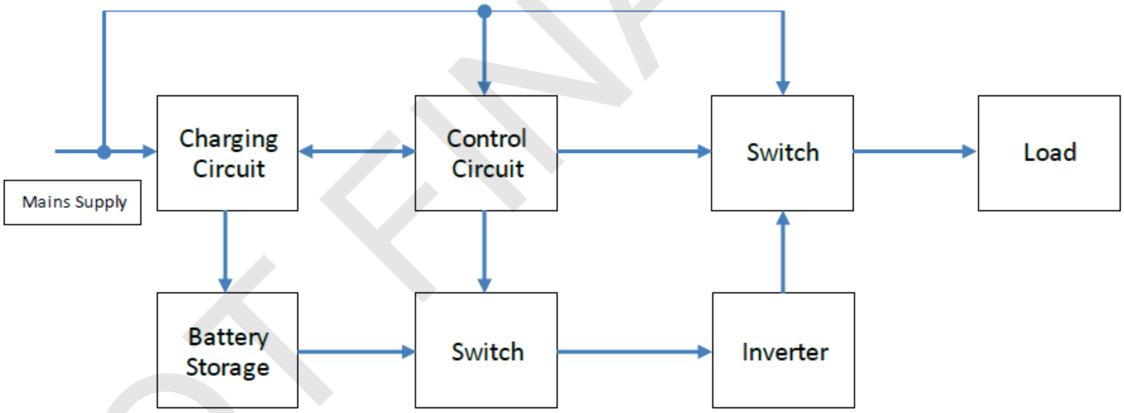

Figure 10.16 Simplified block diagram of a UPS

The control circuit monitors the incoming mains supply for loss of supply or poor power quality (voltage dips, voltage sags, etc.) and replaces the incoming mains supply with the battery-derived inverter output. The size of the battery storage and inverter determines the size and duration of the load that the UPS can supply in the loss of mains supply.

UPS systems are usually configured in one of three different categories:

- **Standby/offline:** a standby UPS only comes into operation once an outage or power quality issue on the mains side is detected. The battery storage is kept fully charged until it is required to supply energy to the load. The block diagram of this configuration of UPS is shown in Figure 10.16.

- **Online:** with an online UPS, the battery-supplied inverter is connected directly to the load. The mains supply is not connected to the load, so the problems on the grid (outage, power quality) do not affect the load. A block diagram of an online UPS is shown in Figure 10.17.

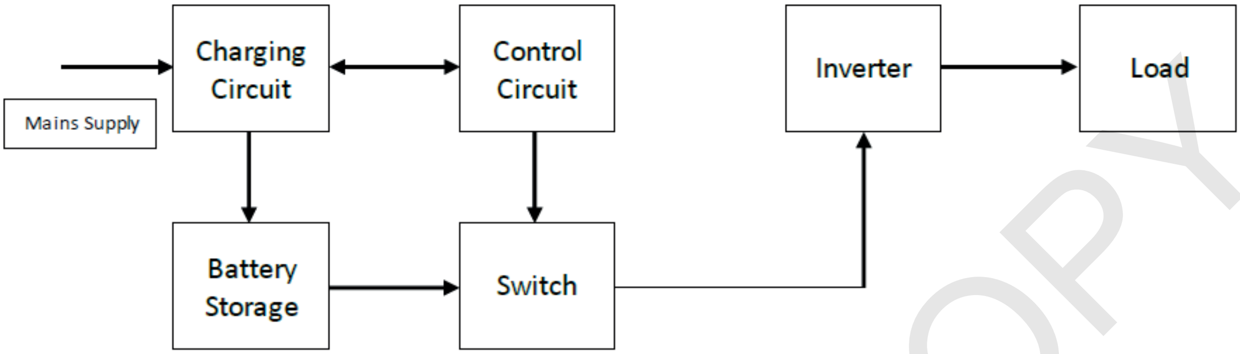

Figure 10.17 Simplified block diagram of an online UPS

- **Line-interactive:** in this UPS configuration, the battery-supplied inverter is only activated when there is a power outage, or large over-voltage, or large under-voltage. For smaller and sustained under-voltage or over-voltage on the mains side, the UPS uses a multi-tap autotransformer, or a buck-boost transformer to increase or decrease the incoming mains supply to compensate for the incoming mains voltage. A block diagram of a line-interactive UPS is shown in Figure 10.18.

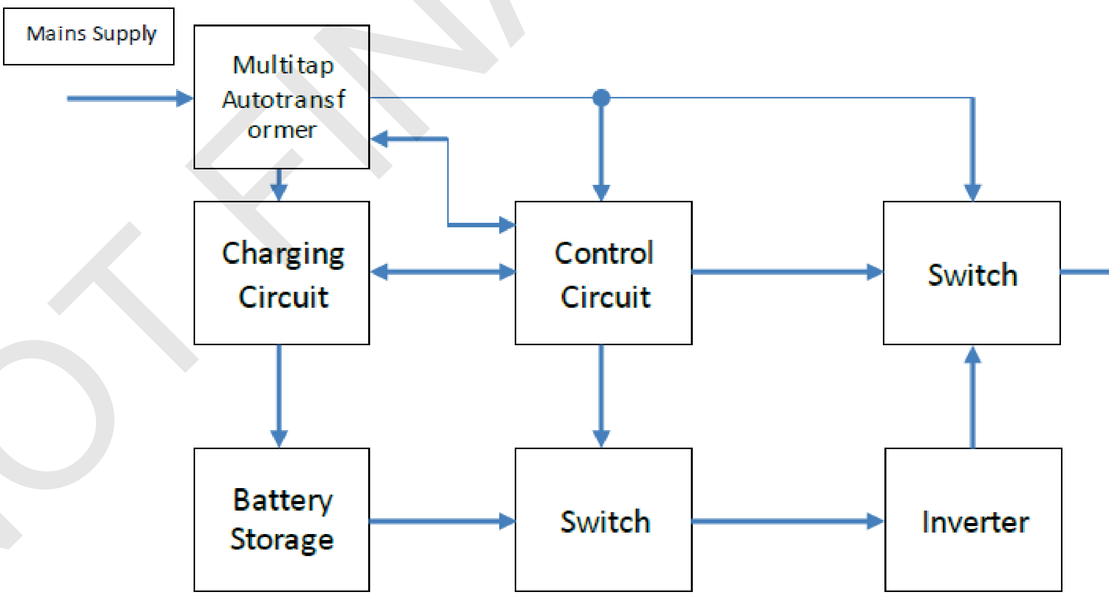

Figure 10.18 Simplified block diagram of a line-interactive UPS

Purpose of a UPS

UPSs are used in cases where one simply cannot have a loss of mains supply, or poor power quality. These cases are known as mission-critical systems. Examples of these include the control room of a nuclear power plant, on-line bank computer servers, airport navigation systems, medical operating theatres, etcetera. UPS systems range from tens of watts for light loads, to kilowatts for heavy loads. Some UPS systems only provide supply for a few minutes. These are sometimes found in computer servers, so that these can save critical data before powering down. They can also be found in places where the UPS provides temporary supply until the main backup generators (typically diesel) are started and stabilised.

Figure 10.19 An example of a mission-critical scenario where a UPS/backup generator ensures continuation of supply

The load requirements will determine the type of UPS and the duration needed for continued supply during an outage. Since battery-based storage systems are very expensive, loads that cannot tolerate sustained power outages are best served by temporary UPS systems, coupled with diesel backup generators. It is much cheaper to run a diesel generator, than a battery of equivalent capacity.

A UPS is an essential part of a grid-tied renewable energy system (see Figure 10.5). If battery storage is employed, the combination of this and the inverter results in a UPS. If there is a loss in the grid supply, the system continues to supply energy to the load.

ACTIVITY 10.2 Mission-critical systems

1. What are "mission-critical systems"?
2. Which of the following scenarios can be deemed as mission-critical?
   a) A bread being baked in a home electrical oven.
   b) A student surfing the internet.
   c) A patient undergoing open-heart surgery.
   d) The control room of a waste-water treatment plant.
   e) A band playing at a restaurant.
   f) A band playing at a large stadium.
   g) The control room of the metro rail network.
2. Use the block diagram of Figure 10.16 as a template to show the energy path from the mains supply to the load for:
   a) normal supply conditions
   b) loss of mains supply.
3. Comparing the three types of UPSs:
   a) Which type has the fastest response time to a supply outage?
   b) Which type provides better immunity from poor supply power quality?
   c) Which types provides good immunity from short duration, small deviations in voltage changes?
4. What is the main difference between an online UPS and a standby UPS?

Module summary

This module dealt with renewable energy with particular emphasis on solar energy and how it can be used to provide us with electrical energy. We also discussed how DC can be converted to AC through the use of an inverter, and how these systems are combined to provide stand-alone PV systems for the home and similar installations.

In particular, we:

- Stated the advantages and disadvantages of solar energy
- Explained how solar energy is converted into electrical energy
- Explained how direct current is converted into alternating current
- Explained what is a UPS
- Explained the purpose of a UPS.

Exam practice questions

1. Draw a block diagram of a standby UPS. (8)
2. Draw the block diagram of an online UPS. (7)
3. Briefly explain the purpose of a UPS. (2)
4. Explain how DC is converted into mains level AC, using an appropriate block diagram. (10)
5. State FIVE disadvantages of solar energy. (5)
6. Briefly explain how solar radiation is converted into electricity in a CSP plant. (4)
7. What is the name of the process that is used to directly convert radiant energy into electrical energy? (1)
8. State whether the following are TRUE or FALSE.
   a) The output of a PV module is an alternating current (AC).
   b) PV modules cannot be connected in series to increase the voltage.
   c) Most CSP plants can generate energy after sunset.
   d) PV-based systems can generate energy after sunset.
   e) PV-based systems emit greenhouse gases during the day.
   f) A PV module is constructed using semiconductor material.
   g) Any periodic, non-sinusoidal waveform will have harmonics.
   h) A perfect sinusoidal waveform will have two harmonics.
   i) A modified sine wave inverter has very few harmonics in its output.
   j) A square wave output from an inverter is also known as a three-step signal.
   k) PWM is a modulation system that changes the amplitude of the carrier signal.
   l) A high pass filter is employed at the output of a PWM-based inverter.
   m) Incandescent lights can be used with inverters having square or modified sine outputs. (13)

Total: 50 marks