# Experiments Manual of Renewable Energy Laboratory


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This publication was produced with the financial support of the European Union. Its contents are the sole responsibility of the partners of IREEDER project and do not necessarily reflect the views of the European Union'

# Contents

# 1. Introduction

This document is an outcome of IREEDER (Introducing Recent Electrical Engineering Developments into undERgraduate curriculum) co-funded by the Erasmus-Plus Programme of the European Union under the Capacity Building of Higher Education Call. IREEDER Project is implemented from November 2019 to November 2022 (3-year project).

The main objective of the IREEDER project is to improve the capacities of high quality education in Jordan, using state of the art technology and training staff on improving the quality of the courses taught by making the best use of these technologies. Specifically, IREEDER aims at introducing the recent developments in Electrical Engineering to the undergraduate curricula, where three subjects in Renewable Energy (RE), Internet of Things (IoT) and Cyber Security (CS) will be developed. Also, three laboratories for training the students in the selected topics will be established in three different Jordanian partners (Universities).

The IREEDER Project is expected to produce three main outputs by the end of the project period, such as:

- Output 1: Teaching materials about the project topics (IoT, CS, RE) accompanied by experimental activities
- Output 2: Establishment of three labs (in three Jordanian universities) related to the project topics, accompanied by a server for a remote lab with virtual lab software at each university of the Jordanian partners
- Output 3: Training workshops in Europe and Jordan

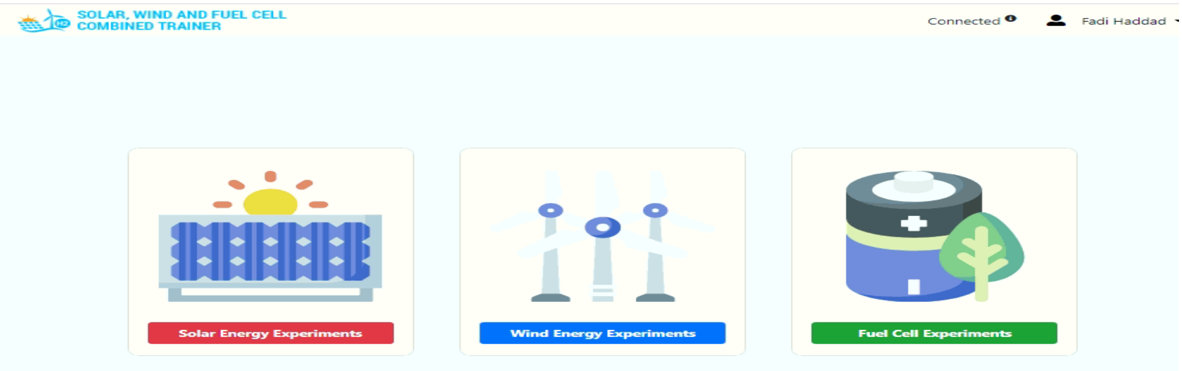
This document represents a training manual for the Renewable Energy Lab of IREEDER project.

Its main contents are collected from the lab sheets of the equipment purchased and installed in IREEDER RE Lab. The training manual is divided into two main parts. The first concerns the training on the power generation modules (Solar, wind and fuel cell), while the other is focused on the PSIM software training.

## 2. Power Generation Trainer Experiments

# *Power Generation Trainer Lab Sheets*

# *Exp No. 1 Power Generation Trainer Guideline*



## 2.1 Experiment No. 1 Power Generation Trainer Guideline

### Introduction

Solar & Wind & Fuel Cell Power Generation Trainer consists of Solar Power Generation, Wind Power Generation and Hydrogen Fuel Cell subtrainers.
The solar power is an unlimited source of energy. It is the technology used to harness the sun's energy and make it useable.

**WHAT IS SOLAR POWER?**
The solar energy, radiation from the Sun capable of producing heat, causing chemical reactions, or generating electricity. The total amount of solar energy incident on Earth is vastly in excess of the world's current and anticipated energy requirements. If suitably harnessed, this highly diffused source has the potential to satisfy all future energy needs.

**HOW DOES SOLAR POWER WORK?**
The solar PV systems use the phenomenon called the photovoltaic effect to convert the light directly into electricity. Devices that use the PV effect to produce electricity from light are called Solar PV panels, or just simply solar panels. PV systems produce direct current (DC) power which fluctuates with the sunlight's intensity and for practical use this usually requires conversion to certain desired voltages or alternating current (AC), through the use of inverters.

**SOLAR POWER BENEFITS**
Among all the benefits of solar panels, the most important thing is that solar energy is a truly renewable energy source. It can be harnessed in all areas of the world and is available every day. Solar energy will be accessible as long as we have the sun, therefore sunlight will be available to us for at least 5 billion years when according to scientists the sun is going to die.
Solar energy can help to reduce the electricity bills. Solar energy can be used for diverse purposes. You can generate electricity (photovoltaics) or heat (solar thermal). Solar energy can be used to produce electricity in areas without access to the energy grid, to distill water in regions with limited clean water supplies and to power satellites in space. Solar energy can also be integrated into the materials used for buildings.

Solar energy systems generally don't require a lot of maintenance. You only need to keep them relatively clean, so cleaning them a couple of times per year will do the job. The solar panel manufacturers offer 20-25 years warranty, and the inverter is usually the only part that needs to be changed after 5-10 years because it is continuously working to convert solar energy into electricity.

**Solar energy benefits:**

- 1.8Gt $CO_2$ emissions avoided through global renewable electricity generation in 2017 – equal to 385 million passenger vehicles driven for one year
- 168,000MW new renewable energy capacity that came online in 2017, an annual increase of 8.3%

- 40% share of electricity generation predicted to come from renewable generation by 2040, nearly double the 21% share in 2017
- Creates wealth and local employment
- Low maintenance cost
- Contributes to sustainable development

Wind is one of the earth's most sustainable natural resources when it comes to generating electrical power.

**WHAT IS WIND POWER?**

Wind power is the use of airflow through wind turbines to mechanically power generators for electric power. Wind power is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation, consumes no water, and uses little land. The net effects on the environment are far less problematic than those of nonrenewable power sources.

**HOW DOES WIND POWER WORK?**

Wind power consists of converting the energy produced by the movement of wind turbine blades driven by the wind into electrical energy.

**WIND POWER BENEFITS**

Wind energy is a source of renewable energy. It does not contaminate, it is inexhaustible and reduces the use of fossil fuels, which are the origin of greenhouse gasses that cause global warming. In addition, wind energy is a “native” energy, because it is available practically everywhere on the planet, which contributes to reducing energy imports and to creating wealth and local employment.

For those reasons, producing electricity through wind energy and its efficient use contributes to sustainable development.

Wind energy does not emit toxic substances or contaminants into the air, which can be very damaging to the environment and to human beings. Toxic substances can acidify land and water ecosystems, and corrode buildings. Air contaminants can trigger heart disease, cancer and respiratory diseases like asthma.

Wind energy does not generate waste or contaminate water—an extremely important factor given the scarcity of water. Unlike fossil fuels and nuclear power plants, wind energy has one of the lowest water-consumption footprints, which makes it a key for conserving hydrological resources.

Wind energy benefits:

- Renewable energy
- Inexhaustible
- Not pollutant
- Reduces the use of fossil fuels

- Reduces energy imports
- Creates wealth and local employment
- Contributes to sustainable development

**WHAT IS A FUEL CELL?**

A fuel cell uses the chemical energy of hydrogen or another fuel to cleanly and efficiently produce electricity. If hydrogen is the fuel, electricity, water, and heat are the only products. Fuel cells are unique in terms of the variety of their potential applications; they can provide power for systems as large as a utility power station and as small as a laptop computer.

Fuel cells can be used in a wide range of applications, including transportation, material handling, stationary, portable, and emergency backup power applications. Fuel cells have several benefits over conventional combustion-based technologies currently used in many power plants and passenger vehicles. Fuel cells can operate at higher efficiencies than combustion engines, and can convert the chemical energy in the fuel to electrical energy with efficiencies of up to 60%. Fuel cells have lower emissions than combustion engines. Hydrogen fuel cells emit only water, so there are no carbon dioxide emissions and no air pollutants that create smog and cause health problems at the point of operation. Also, fuel cells are quiet during operation as they have fewer moving parts.

**Web Development Start:**

Please Sign in using your Username & Password, if you don't have a Username & Password yet, please click on Sign Up in order to create one and then go to the Main page.

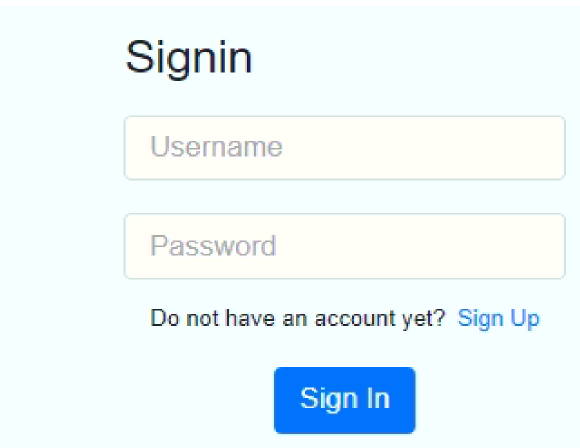



*Figure 2-1 Training Module Sign In Screen*

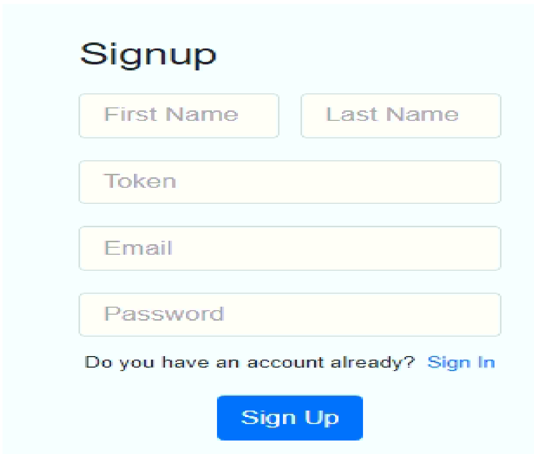



*Figure 2-2 Training Module Sign Up Screen*

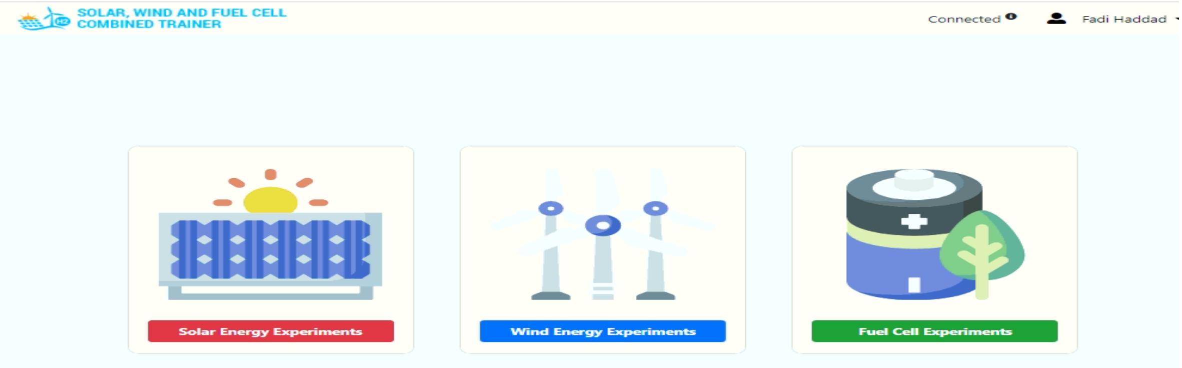


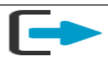

*Figure 2-3 Training Module Main Page*

## Remote Lab Access

Use the following URL to access the RE lab remotely:

- http://87.236.232.233/ (outside Mutah University)
- http://10.235.164.114/ (inside Mutah University )

### MAIN MENU ELEMENTS:

| Icon | Description |
|---|---|
| SOLAR & WIND & FUEL CELL POWER GENERATION TRAINER | navigates to the home page |
| HOME | defines the path line |
| Disconnected<br>Connected | shows the Connected/Disconnected mode of the myRIO device inside the Control and Measurement Module. |
|  | opens the Image deployment |
|  | navigates to the Solar & Wind & Fuel Cell Power Generation Trainer Laboratory Manual.pdf |
|  | minimizes the software |
|  | closes the software |

***Power Generation Trainer Lab Sheets***

# *Exp No. 2 Solar Power Trainer: Structure and design of a solar photovoltaic power plant*

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## 2.2 Experiment No. 2 Structure and design of a solar photovoltaic power plant

### Introduction

The solar power plant converts the energy of solar radiation into electrical energy.
There are various ways to convert the solar energy into electrical energy and consequently, there are various types and schemes of solar power plants. The most common conversion methods and the corresponding types of solar power plants are listed below.
The conversion of solar energy into electrical energy is carried out in two fundamentally different ways:

1. The direct conversion of solar energy into electrical energy through photovoltaic converters.
2. The generation of electrical energy through the conversion of solar energy into thermal energy and further conversion of thermal energy into electrical energy by traditional means through heat engines and electric machine generators.

Accordingly, there are the following types of solar power plants:

**Photovoltaic power plants**

The Photovoltaic power plants directly convert the solar energy into electrical energy through the photovoltaic converters. The operational principle of the photovoltaic power plant is based on the use of an internal photovoltaic effect in semiconductors. The structure of a silicon photovoltaic converter with a P-type (positive) and N-type (negative) semiconductor is shown in **Figure 2.4.**

When the sun is irradiated to the solar cell surface, an electrical voltage of *0.5 V DC* is generated at the electrical outlets of the P-type and N-type surfaces, and an electrical current arises when the load is connected to the circuit. The photo elements are made as flat photo-conversion cells. The cells, in their turn, connected with each other, form the photovoltaic panel or solar module. The electrical outputs of the photocells and panels are connected in series and in parallel so that the output of the solar battery produces the necessary DC voltage of a given power. The power in the solar power plant is determined by the number of photo-converting cells used.

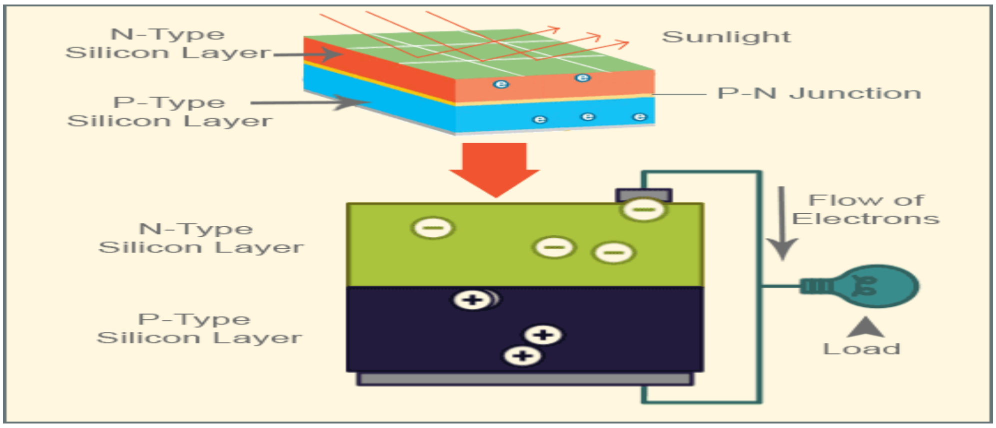



*Figure 2-4 The structure of a silicon photocell of the photovoltaic converter*

General view of solar photovoltaic panels is shown in **Figure 2.5**. The Photovoltaic panels are mounted on the roofs of houses or in open areas. To increase the power generation and increase the efficiency of a power plant, in some cases, special systems can be mounted with the possibility to change the orientation of panels across the Sun by means of automatic devices for tracking the position of the Sun and mechanically reorienting the position of the panels.

*Figure 2-5 Photovoltaic panels*

The operational feature and the power supply of a photovoltaic power plant is the incompatibility of daily energy schedules - the solar radiation schedule and the power consumption schedule.

**The implementation of this principle in power plants in on-grid mode differs from the ones in off-grid mode:**

**1- Solar power plants operating in off-grid mode supplying a load**

Those types of solar power plants are usually used for low-power facilities and, accordingly, have low power. The electrochemical batteries are used to store the energy in those kind of power plants. The energy generated by the solar panels in the daytime is used to power its own consumers; the energy, produced above this, charges the battery and is accumulated in it. In the night time when the solar power generation is absent or insufficient, the power is supplied to the consumers from the accumulated energy through the inverter, which converts the battery's DC voltage to AC with standard frequency and a sinusoidal voltage.

The structure of a solar power plant in off-grid mode supplying a load is shown in **Figure 2.6**.

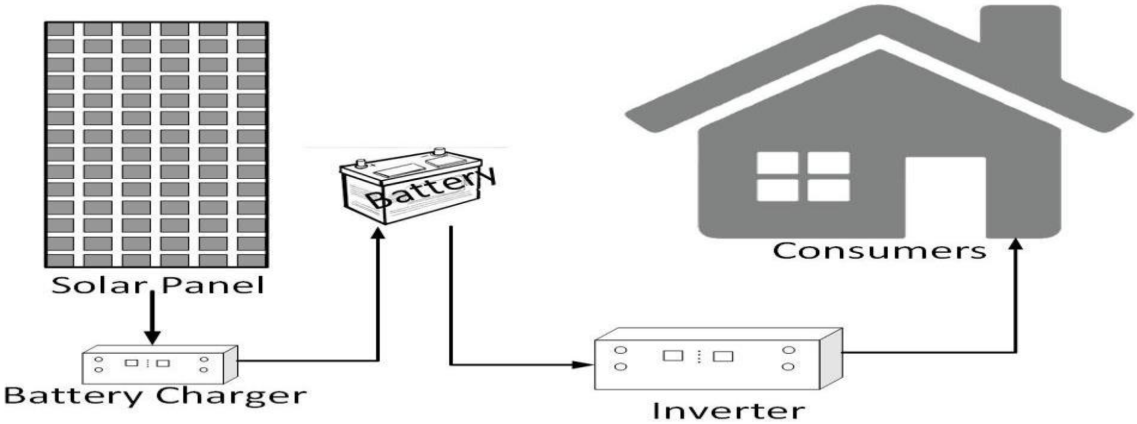



*Figure 2-6 The structure of off-grid photovoltaic power plant*

**The Solar Panel** converts the solar energy directly into DC electrical energy.
**The Battery** is charged with the current generated by the solar photovoltaic panel through the charger, and accumulates energy.
**The Battery Charger** automatically adjusts the battery charging current value, depending on the charge level of the battery, its voltage and voltage on the solar panel.
**The Inverter** converts the battery's DC voltage to a sinusoidal AC of standard frequency and voltage.
The accumulated energy in the battery through the inverter in the form of alternating current of sinusoidal form of standard frequency and voltage is supplied to the consumer.

## 2- Solar power plants operating in on-grid mode

In solar power plants of this type, an industrial electrical network is used as a battery of the generated energy. It is implemented in the following way:
The energy generated by the solar panels in the daytime supplies its own consumers; The unused energy, produced above this, is transmitted directly to the industrial electrical network, where it is used by network consumers.

In the night time, the energy is taken from the industrial network to supply its own consumers. Thus, there is a certain balance between the energy transmitted to the network and the energy received from the network. This balance can be positive - if the energy transferred to the network is greater than that taken from the network, or negative - if the energy transferred to the network is less than that taken from the network. This difference is paid, respectively, either by the network of the power plant, or by the power station of the network at the existing tariffs.
Batteries are not used in solar power plants of this type, respectively, there is no battery charger. However, the inverter is equipped with network synchronization and regulation devices.
The structure of solar power plants operating in on-grid mode is shown in **Figure 2.7.**

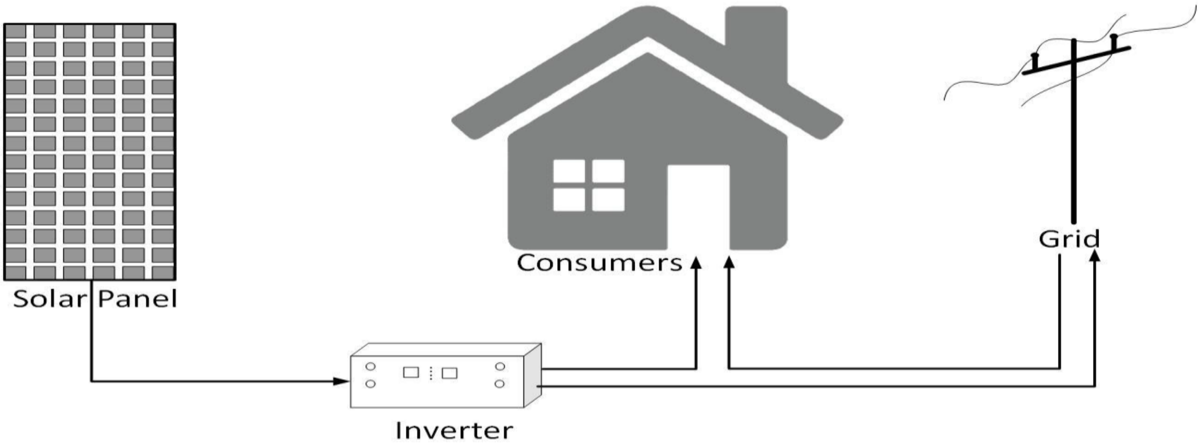



*Figure 2-7 The structure of an on-grid photovoltaic power plant*

### 3- Solar tower power plants :

In power plants of tower type, the energy is generated by an intermediate conversion of solar energy into thermal energy and further conversion of thermal energy into mechanical and electrical energy through a steam turbine and a turbo electric generator connected to it.
Those kind of power plants are based on the principle of obtaining high-temperature water vapor using solar radiation. The power plant operates in a closed steam-water cycle. In the center of the station, a tower is installed with a height of 18 to 24 meters, on top of which there is a water tank (**Figure 2.8**). The tower also contains a pumping unit that delivers water to the tank. The turbo power unit is outside the tower.

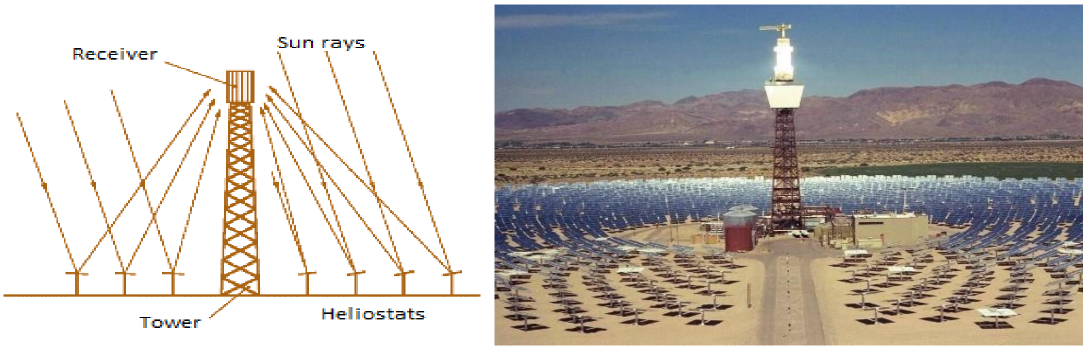



*Figure 2-8 Solar towel power plant*

At a certain distance from the tower, the heliostats are arranged in a circle. A heliostat is a flat mirror with an area of several square meters, fixed on a pole and connected to the general positioning system. Depending on the position of the sun, the heliostats' orientation of the sun automatically changes, so that the solar radiation is always concentrated on the tank at the top of the tower. As a result, the water in the tank heats up and changes to the vapor mode with a high temperature of steam. In a clear sunny weather, the temperature in the reservoir can reach up to 700 ºC, which leads to the formation of high-temperature of high-pressure steam. Such temperature parameters are used at most traditional thermal power plants; thus, standard turbines and turbine generators are used to generate energy. At those kind of power plants, relatively high values of efficiency can be obtained - approximately 20% and capacities of the order of up to several tens of megawatts and above.

Currently, solar power plants of tower type with a capacity of more than 100 MW are being developed; the area occupied by the mirrors of such solar power plants is several hundred hectares.

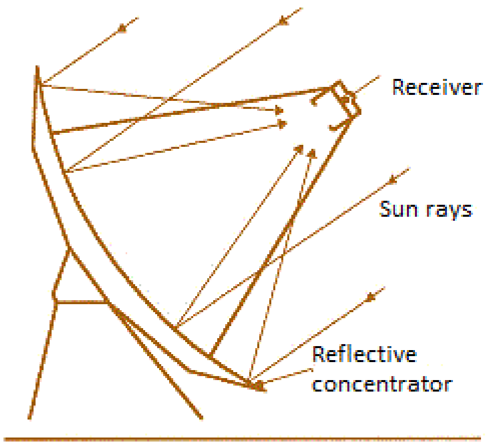
Tower-type solar power plants have certain advantages compared to other types of power plants:
- have a higher efficiency,
- have the inertia of energy transfer, which allows to generate electricity for some time due to the accumulated high-temperature steam for cloudiness and a decrease in the intensity of solar radiation.

The unit cost of tower-type solar power plants is higher than other types of power plant.

**4- Solar power dish-shaped type :**

Those types of solar power plants use the principle of generating electrical energy, similar to solar tower power plant, but there are differences in the design of the power station itself.

The power station consists of separate modules. The module consists of a support structure on which the truss structure of the receiver and the reflector is mounted. The receiver is located in the area of concentration of the reflected solar radiation. The reflector consists of a mirror in the form of a satellite dish (hence the name of the power station), which captures the solar energy on a receiver located at the focus of each dish (**Figure 2.9**). The fluid in the receiver heats up to 1000° C.



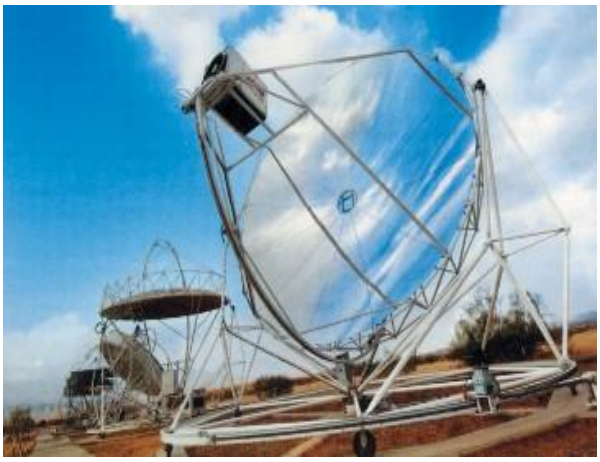



*Figure 2-9 Solar power dish-shaped type*

**5- Solar power plants using parabolic-cylinder concentrators :**

In solar power plants of this type, the parabolic-cylinder concentrators are used as a solar heating element (**Figure 2.10**). The parabolic cylinder concentrators consist of a long length mirror with a parabolic cylinder reflecting surface, a tube (installed at the focal point of the parabola), through which the coolant is pumped - most often oil. After going all the way, the oil is heated to about 400° C. Further, in the heat exchangers, the heated oil gives off heat to the water, where the water is converted into high-temperature and high-pressure steam, the steam enters the turbo-generator, where the electrical energy is generated according to the traditional scheme.

The concentrators are automatically positioned on the Sun through an automatic tracking system

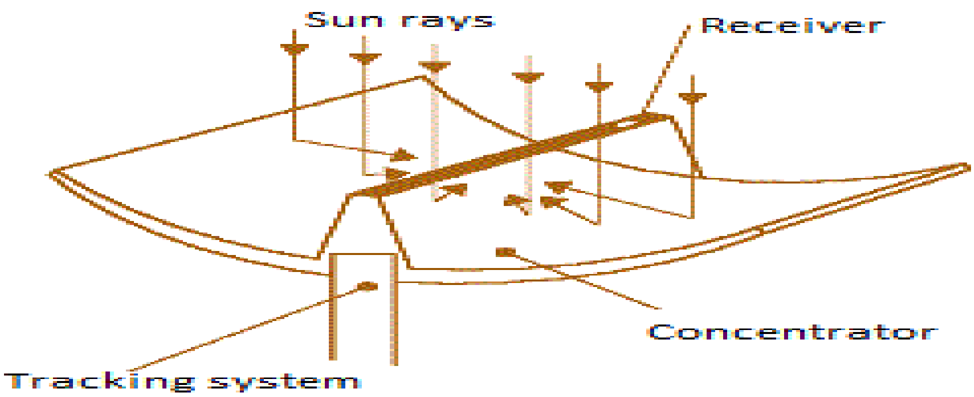



*Figure 2-10 Diagram of the parabolic-cylinder concentrator*

The Parabolic type solar power plants are being used more and more due to a simpler system for tracking the Sun and less material intensity. The unit cost of parabolic-type stations is close to the unit cost of nuclear power plants.

## Objectives

1- Get acquainted with solar power plants of various types

2- Studying the operating principles, the structure and design of a solar photovoltaic power plant. The study of the operation of a photovoltaic power plant is performed on the educational trainer which simulates a real solar power plant.

3- The educational trainer simulates a real solar photovoltaic power plant of on-grid operation or off-grid operation supplying a separate load, with the possibility of stabilization and regulation of the main parameters of the power plant and the load.

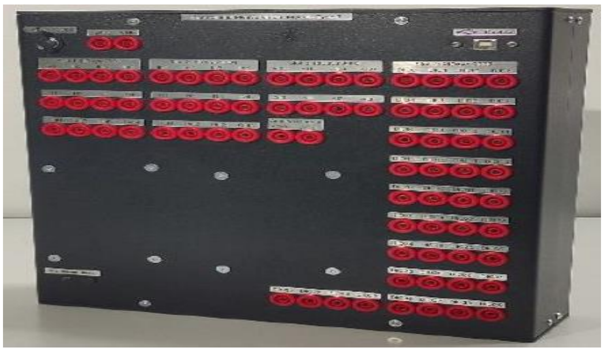
**Experiment Components:**

**PV Panel Module:** The PV Panel Module consists of the following components:

| | |
|---|---|
|  | **PV Panel Module**<br>**18V, 60W PV panel, type-monocrystalline** |
|  | **Halogen lamps**<br>**18X150W** |
| <br> | **Fan – quantity (2)**<br>**Solar Sensor Block**<br>This module handles the movement of the PV panel and the Sun Simulator and provides the output of the PV panel and the sensors. It allows to control the position of the PV panel and the Sun Simulator from the software. |

| | |
|---|---|
|  | **Solar Irradiation Sensor**<br><br>**Measurement range**<br><br>**0-2000W/m2** |
|  | **Charge Controller Module Type 1**<br><br>The AC charge controller is used for charging the Battery Module in Wind trainer. This module is responsible for accurate charging process and for battery protection from overcharge. It also implements voltage regulation function. |
|  | **Charge Controller Module**<br>The DC charge controller is used for charging the Battery Module in Solar trainer. This module is responsible for accurate charging process and for battery protection from overcharge. It also implements voltage regulation function |
|  | **Battery Module**<br>The battery is a small capacity battery, which will be charged by a charge controller module. The battery is used to accumulate energy in case it's needed in no-wind or no-sun cases. |
| | **DC to AC Inverter Module**<br>This pure sinewave inverter is used to convert the generated DC voltage to AC voltage. It has built-in short-circuit |

| | |
|---|---|
|  | protection, and battery undervoltage protection. |
|  | **RLC Load Module**<br>This is a complex load module containing different types of loads. Each type has three stages |
|  | **AC/DC Transformer Module**<br>This module is designed to transform an alternating single-phase voltage of a 220 V supply network into a single-phase voltage of 12 V. It includes a circuit breaker with thermal protection against short circuits. |
|  | **Power Supply Module**<br>This module supplies power to the other modules used in each experiment. It is switched on by a key and has short circuit protection. The input of the module is single-phase |

| | |
|---|---|
|  | **Control and Measurement Module**<br>The module is based on NI myRIO platform. It combines voltage and current input, digital input/output modules. It may optionally include different software modules like Power Quality Analyzer (PQA), Microprocessor Relay Protections (MRP), Automatic Transfer Switch (ATS) and Synchronizer. This trainer includes only the PQA module. |

### *Step by Step Instructions:*

In order to start operating the following steps should be implemented:

1. Turn on the computer.

2. Place the components on the Mounting Frame (**Figure 2.11**) with the following order:

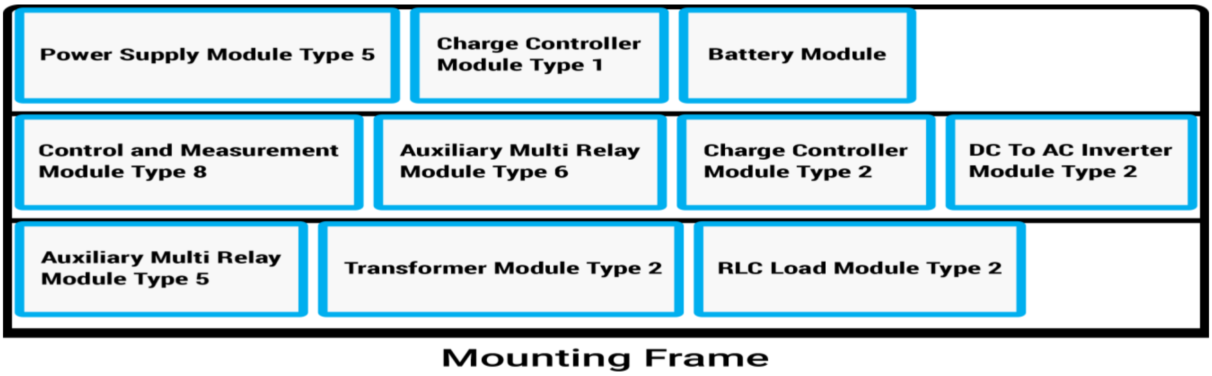



*Figure 2-11 Mounting Frame*

3- After completing the appropriate wiring, please switch the power cable of the *Power Supply Module Type 5* to the power socket and switch the key of the *Power Supply Module Type 5* to turn in ON. Make sure the built-in circuit-breakers in the components are ON.

## Questions:

1. In case of solar power plants operating in off-grid mode, a battery is used to:

   a. increase daily power generation

   b. stabilize the output voltage

   c. power the consumers with insufficient solar radiation

2. When the angles of incidence of sunlight on the surface of the solar panel deviate from the perpendicularity of the panel, the voltage :

   a. Decreases

   b. Increases

   c. remains unchangeable

3- In case of the solar power plants with intermediate thermal cycle, the following energy conversion occurs:

   a. solar-electrical

   b. solar-thermal-mechanical-electrical

   c. solar-thermal

4. The invertor converts:

   a. The DC voltage to AC

   b. The AC voltage to DC

   c. The DC voltage to DC voltage of another voltage

5. Describe the operating principles of a solar towel power with an intermediate thermal cycle?

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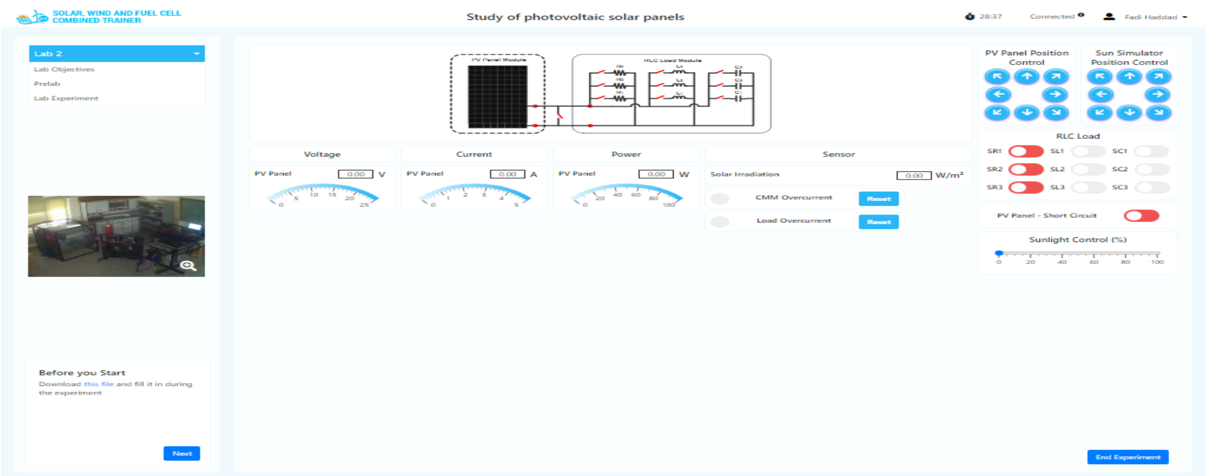
# Power Generation Trainer Lab Sheets

## *Exp No. 3 Solar Power Trainer: Study of photovoltaic Solar Panels*

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## 2.3 Experiment No. 3 Study of photovoltaic solar panels

***Introduction:***

In case of photovoltaic power plants, the electrical energy is generated through the direct conversion of solar energy into the electrical energy with PV cells. The operational principle of the photovoltaic converter is based on the use of an internal photovoltaic effect in semiconductors. The structure of a silicon photovoltaic converter with a semiconductor p-n type structure . When the solar cell irradiates the surface of the PV cell, an electrical voltage of the p-type and n-type surfaces generates an electrical voltage of 0.5 V DC, and when the load is connected, an electric current arises. The PV cells are structurally mounted in the form of flat PV panels . The panels, in their turn, are interconnected and represent a solar panel or solar module. The electrical outputs of the PV cells and panels are connected in series and in parallel so that the output of the solar battery produces the necessary DC voltage of a given power. The magnitude of a power station is determined by the number of used PV cells.

With the intensive solar irradiation in clear weather, the silicon PV cells produce an electric current of about 25 mA at a voltage of 0.5V per square centimeter of the cell area, that is, 12–13 $mW/cm^2$. This corresponds to a power of 120–130 $W/m^2$ of panel surface when the corresponding load is switched on. The theoretical efficiency of silicon solar cells (efficiency, expressed as the ratio of generated electric power to the power of solar radiation) in normal environmental conditions is about 28%, practical - from 14 to 20%.

The efficiency of silicon PV cells under the influence of the natural and climatic conditions in which the cells operate, is greatly reduced. To overcome those negative effects, in some cases, the appropriate measures are taken. The power of a solar power plant is determined by the actual power of the PV cells operating under those conditions - their real efficiency.

**The main natural impacts that affect the efficiency of the silicon solar PV cells are as follows:**

**1. The ambient and solar cells' temperature**

The efficiency of a solar cell largely depends on its temperature. The temperature of the solar cell is determined by the following two effects:

a. The ambient temperature, which determines the initial temperature of the PV cell

b. The temperature overheating of the PV cell which is caused by the current flow in the cell, respectively, with selected losses and heating of the cell.

The absolute temperature of the PV cell is equal to the sum of those two temperatures.
In summer, when the ambient temperature is high and the current consumed in the cell is high, the cell temperature reaches to about 70º and higher. This leads to decrease in efficiency for about

20%. Moreover, the decrease in efficiency to a greater extent occurs at high loads of the power plant, when a higher current is produced in the PV cells and, accordingly, the own overheating is high.
In winter, the temperature of the cell reaches to about 40º. This leads to a decrease in the efficiency for about 7–8%.
In order to reduce its own overheating and limit the decrease in efficiency, forced cooling of PV panels is used.
In the Solar Power Generation Trainer, the cooling of PV panels is performed with two fans that are mounted on the panel.

**2. Changing the angle of solar incidence radiation to the surface of the PV panel**
When the Earth moves around the Sun and the Earth rotates around its axis, the angle of solar incidence flux on the solar panel (which is normally installed on the Earth's surface), changes.

The change of the solar incidence angel on the solar panel is caused by the following factors:

a) the seasonal angle change during the year due to the movement of the Earth around the Sun and the tilt of the axis of rotation of the Earth relative to the Earth's rotation planes around the Sun
***b)*** the daily angle change during the day time due to the rotation of the Earth around its axis.

**Table 2.1** shows the declination angles of the Sun above the horizon, depending on the days of the year:

*Table 2-1 The declination angles of the sun above the horizon (φ) depending on the days of the year*

| The Days | Declination of the Sun | The Days | Declination of the Sun |
|---|---|---|---|
| January 21 | -20° | June24 | +20° |
| February 8 | -15° | August 12 | +15° |
| February 23 | -10° | August 28 | +10° |
| March 8 | -5° | September 10 | +5° |
| March 21 | 0° | September 23 | 0° |
| April 4 | +5° | October 6 | -5° |
| April 16 | +10° | October 20 | -10° |
| May 1 | +15° | November 3 | -15° |
| May 21 | +20° | November 22 | -20° |
| June 22 | +23.5° | December 22 | -23.5° |

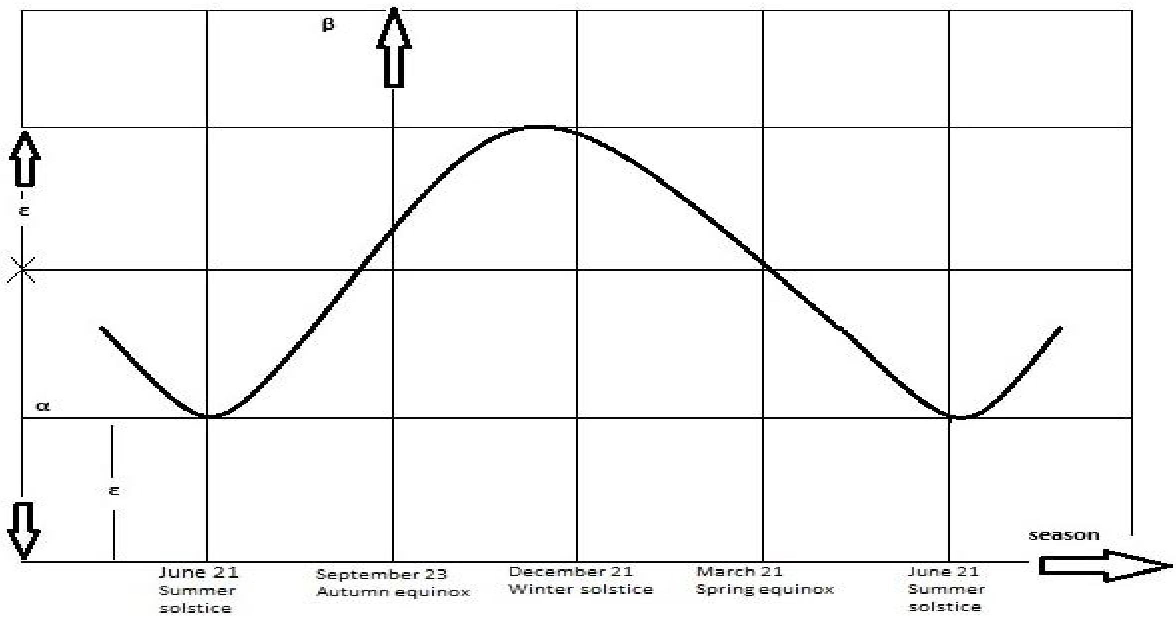



*Figure 2-12 Changing the angles of rotation of the solar panel when the Earth moves around the Sun*

**3) Reduction of the luminous flux falling on the solar conversion panels**

The solar stream, falling on the surface of the solar panel, passes through the layer of the atmosphere. This layer of the atmosphere is a filter - a certain resistance to the light flux, which reduces the intensity of irradiation of the solar panel.

The amount of atmospheric resistance and, accordingly, a decrease in the intensity of irradiation of the panel, depends on the following natural factors.

a- The thickness of layer of the atmosphere through which the solar stream passes.

b- Increasing the distance from the Earth to the Sun as the Earth moves in an orbit around the Sun.

c- Cloudiness in the atmosphere.

d- Humidity, which is characterized by the presence of vapor or particles of moisture in the atmosphere or in the surface area of the solar panel.

e- Dustiness, which is characterized by the presence of solid particles in the atmosphere or in the surface area of the solar panel.

***Objectives:***

- Study and characterization of the photovoltaic panels

### *Experiment Components:*

- **PV Panel Short-Circuit** – it is used to short circuit the output of the PV panel.

**Sunlight Control (PV Panel Module)** – the user can control the sunlight intensity which is measured in %.

**RLC Load Module includes**:

SR1, SR2, SR3 switches – switches ON and OFF each stage of the Resistive load

SL1, SL2, SL3 switches – switches ON and OFF each stage of the Inductive load

SC1, SC2, SC3 switches - switches ON and OFF each stage of the Capacitive load

***If the switches are disabled, it means those are not used in that specific experiment.***

- **Load Overcurrent** – indicates whether there is an overcurrent in the load's section. In case of overcurrent, the indicator lights up to orange.
- **Overcurrent Reset** – resets the overcurrent. It is used when the 'Load Overcurrent' indication is orange.
- **PV Panel Position Control** - the user can move the position of the PV Panel pressing the respective arrows
- **Sun Simulator Position Control** - the user can move the position of the Sun Simulator pressing the respective arrows
- **Control and Measurement Module block includes**:
  - **Voltage (PV Panel)** – shows the voltage value of the PV Panel
  - **Current (PV Panel)** – shows the current value of the PV Panel
  - **Power (PV Panel)** – shows the power value of the PV Panel
- **Sensor (Solar Irradiation)** - shows the solar irradiation generated by the solar simulator
- **CMM Overcurrent** – indicates whether there is an overcurrent in the CMM's section. In case of overcurrent, the indicator lights up to orange.
- **Overcurrent Reset** – resets the overcurrent. It is used when the 'CMM overcurrent' indication is orange.

### *Application Software Description*

**Figure 2.13** shows the screenshot of Lab 2

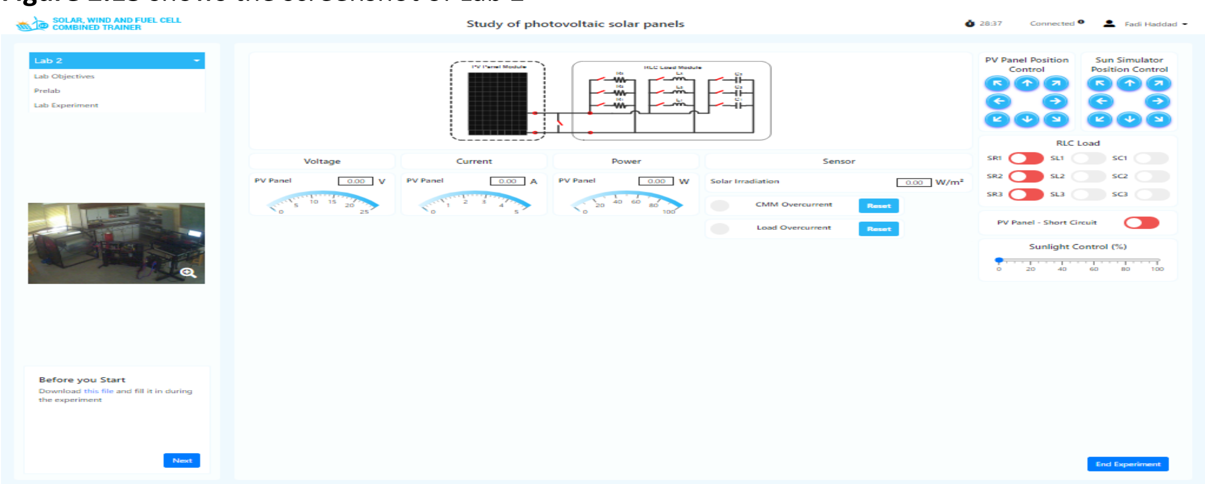


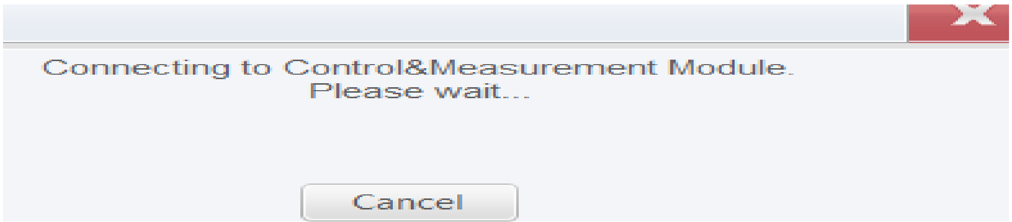

*Figure 2-13 Screenshot of Lab 3*

**Step by Step Instructions:**

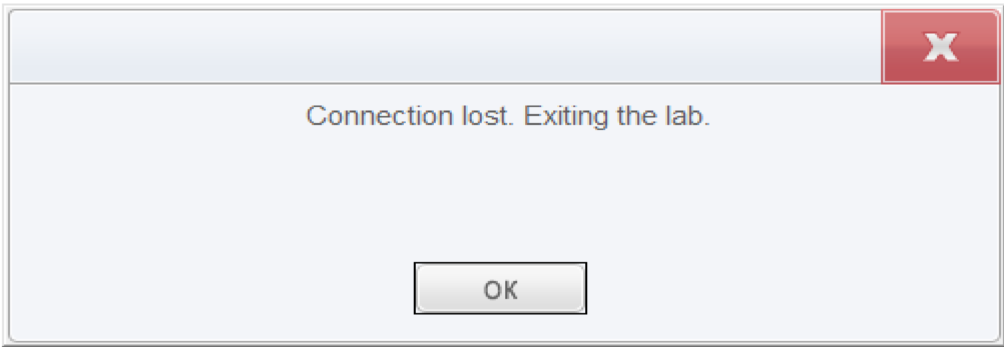
1. Open Lab 2 in the software
2. In case myRIO device inside the Control&Measurement Module has not been connected yet, the below pop up appears on the screen1 and on the top right corner of the screen it shows

Disconnected

The user should wait until it gets connected.




When the system is running, at any point of time when the myRIO device inside the Control &Measurement Module is disconnected, the below pop-up appears on the screen2. When you press OK, the software goes back to Home page.




**The Solar panel has the following parameters**:

- open circuit nominal voltage which is 18 V DC
- nominal irradiation, which provides open circuit nominal voltage,
- short-circuit current, which is provided at nominal irradiation,
- nominal power, which is provided at nominal irradiation and at which the panel temperature does not exceed 70°.

**In this lab, the following characteristics will be determined.**

- **Task 1** :The idling characteristic
- **Task 2:** The short circuit characteristic.
- **Task 3:** The load characteristic
- **Task 4**: The dependence of voltage and power on irradiation.

3. Move the array of halogen lamps to a position perpendicular to the PV panel in both X and Y axes using the PV Panel Position Control and the Sun Simulator Position Control from the software.
4. Switch OFF all SR switches on the RLC Load Module.
5. Set 0% on the Sunlight Control.
6. After completing all the tests (N 1…4) set the Sunlight Control to 0% from the software.
When implementing the tests (NN 1 … 4) do the following steps.

### *Experiments:*

**Task 1: The idling characteristic**

Idle mode characteristic is the dependence between the voltage produced by the PV panel and the applied solar irradiance.

1. Determine the idle mode characteristic and the nominal irradiation the following way.

2. Turn off the switches of the *RLC Load Module.*

3. Gradually and smoothly increase the Sunlight Control (%) from the software and fix it in several positions. In each position determine the:

- **Solar Irradiation** – by getting the value measured by the pyranometer installed on the PV panel Voltage
- **voltage** – produced by the PV panel.

4- Save the results in **Table 2.2** .

*Table 2-2 Idle Mode characteristic*

| | | | | | |
|---|---|---|---|---|---|
| Solar Irradiation | | | | | *Sn max =* |
| PV Panel Voltage | | | | | *Un max =*13,2 *V* |

5- Determine the nominal irradiation at which the PV Panel Voltage produced by the PV panel is equal to the nominal 18 V with an acceptable deviation from the upward side by 10%, i.e. 19.8 V. This amount of Solar Irradiation is considered as the nominal. Remember this value for the next experiments.

**Based on the results in the Table 2.2, draw the idle mode characteristic, which is the dependency of PV panel voltage and applied irradiation.**

**Task 2: The short circuit characteristic**

Short-circuit characteristic is the dependence between the short-circuit PV Panel Current of the PV panel and the applied solar irradiance.

1. Determine the short-circuit characteristic and the short-circuit irradiation the following way.

2. To achieve a short-circuit, switch the PV Short-Circuit from the software.

3. Gradually and smoothly increase the Sunlight Control (%) from the software and fix it in several positions. In each position determine the:

- **Solar Irradiation** – by getting the value measured by the pyranometer installed on the PV panel
- **short-circuit current** – PV Panel Current

4. As a maximum PV Panel Current, it is considered the short-circuit current at a nominal irradiation

5. Save the results in **Table 2.3**

*Table 2-3 Short-circuit characteristic*

| | | | | | |
|---|---|---|---|---|---|
| Solar Irradiation | | | | | *Sn max* = |
| PV Panel Current | | | | | *Un max* =13,2 *V* |

6. Determine the amount of PV Panel Current at nominal irradiation. Nominal irradiation is the Solar Irradiation at which the produced PV Panel Voltage in idle mode is equal to 18V. This value is determined in the previous test.

7. Switch off the PV Panel Short-Circuit from the software.

**Based on the results in the Table 2.3, draw the short-circuit characteristic, which is the dependency short-circuit current of PV panel and applied irradiation.**

### Task 3: The load characteristic

Loading characteristic is the dependence between the PV Panel Voltage and the PV Panel Current and PV Panel Power at the nominal solar irradiance. It is determined the following way:

1. Before connecting the load, obtain a nominal irradiation using Sunlight Control (%) from the software.

2. Switch ON the switches of *RLC Load Module* in order. As the load increases the PV Panel voltage decreases and the PV Panel Temperature increases. At each position determine the:

- **PV Panel Voltage,**
- **PV Panel Current,**
- **PV Panel Power**,

3. The maximum PV Panel Current is considered the current at the nominal irradiation

4. Save the results in **Table 2.4**

*Table 2-4 Loading Characteristic*

| | | | | | |
|---|---|---|---|---|---|
| PV Panel Voltage | | | | | *Un max* =13,2 *V* |
| PV Panel Current | | | | | *I max* = |
| PV Panel Power | | | | | *P max* = |

**Based on the results in Table 2.4, draw the loading characteristic, which is the dependency of PV panel Voltage and current within the idle mode and maximum loading.**

***U = f (I, P)* when *Sn max = const***

**Task 4: The dependence of voltage and power on irradiation:**

This dependency is determined as a loading characteristic with a varying irradiation. It is determined the following way.

1. Set the maximum irradiance using the Sunlight Control (%) from the software.

2. Obtain maximum PV Panel Current by switching ON all the SR switches of the *RLC Load Module.*

3. Gradually decrease the Solar Irradiation using the Sunlight Control (%) from the software by fixing it in several positions. At each position determine the:

**- PV Panel Voltage,**
**- PV Panel Current,**
**- PV Panel Power,**

4. Save the results in **Table 2.5**

*Table 2-5 Dependency of voltage and power from irradiation*

| | | | | | |
|---|---|---|---|---|---|
| Solar Irradiation | | | | | *Sn max* = |
| PV Panel Voltage | | | | | *Un max* =13,2 *V* |
| PV Panel Current | | | | | *I max* = |
| PV Panel Power | | | | | *P max* = |

**Based on the results in the Table 2.5, draw the dependency of PV panel voltage, current and power from solar irradiance.**

***U, I, P = f (S).***

## Questions:

1. With a decrease in the latitude of the installation site of the solar panel in its fixed position, the produced energy :

a. Increases

b. Decreases

c. Remains unchangeable

2. As the load increases, the voltage on the solar panel :

a. Increases

b. Decreases

c. Remains unchangeable

3. The maximum energy can be produced in case of :

a. spring equinox

b. summer equinox

c. at the apocenter July 3

4. As the temperature of the solar panel increases, the voltage of the panel :

a. Increases

b. Decreases

c. Remains unchanged

**<u>Instructions for Preparation of Lab Report</u>**

Before preparing your report, complete the tasks and answer questions throughout the lab sheet.

YOUR Report <u>must</u> include:

- Introduction: A brief about the experiment
- Material and Methods/ Procedure
- Analysis
- Results and Discussion
- Conclusions

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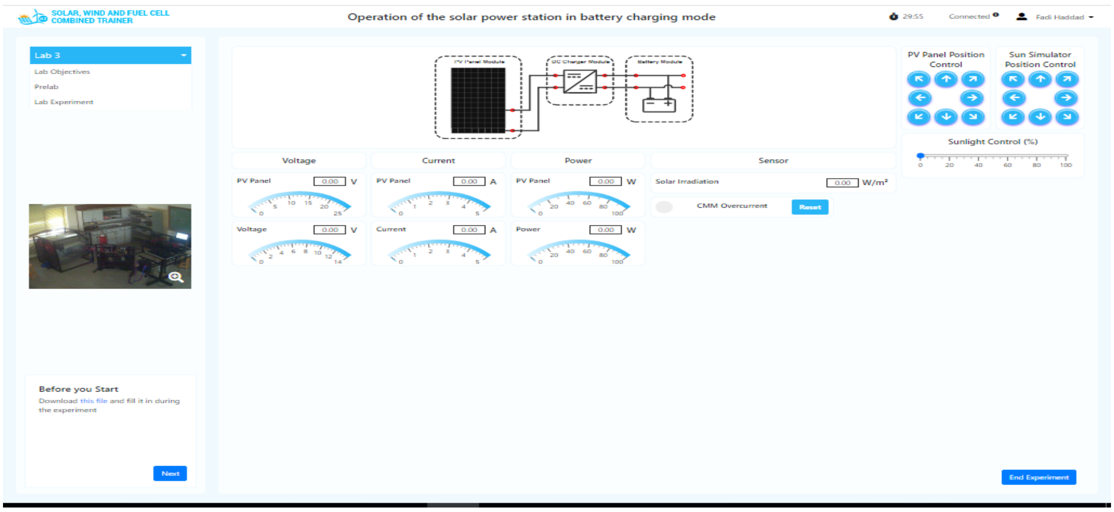
# *Power Generation Trainer Lab Sheets*

## *Exp No. 4 Solar Power Trainer: Operation of the solar power station in battery charging mode*

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*Saud Althunibat*

## 2.4 Experiment No. 4 Operation of the solar power station in battery charging mode

### Introduction:

The solar power plant can operate in battery charging mode supplying a load. In this case, the electricity generated by the power plant is used to power autonomous consumers not connected to the grid. The power consumption is always equal to the power generated by the power plant. (The power losses in the electrical equipment and cable connections are related to power consumption.)

The power consumption is arbitrary - it is determined by the number and power of the connected consumers; the power that a solar power plant can generate is determined by the intensity of solar radiation - this power depends on external conditions and is practically unregulated. Therefore, there is always an inconsistency between the required power consumption and the possible generation power. Usually, in the sunny time of the day, the power of the possible generation is greater than the power of consumption; in twilight or dark time of day, the power of generation is small or equal to zero, and the power of consumption, on the contrary, increases. In such conditions, the use of a solar power plant to power autonomous consumers is possible only for a short time with low efficiency and is practically excluded.

The way out of this situation and the real possibility of using a solar power plant to power autonomous consumers is to use an electric energy accumulator. An electric battery is connected at the output of the solar panels via a charge controller. The battery is an additional power consumer in the power plant at daytime, when there is an excess of generating power relative to the power consumption - then the battery is intensively charged and accumulates electricity; At the same time, the generation efficiency increases. In the twilight or dark time of the day, when there is a lack of generation power relative to the consumption power, the battery feeds the consumers with accumulated electric energy through the existing inverter.
The structure of a solar photovoltaic power plant in off-grid operating on a separate load is shown in **Figure 2.14**.

The battery charger automatically adjusts the charging current of the battery depending on the type of battery, the degree of charge of the battery, its voltage and the voltage on the solar panel. The inverter converts the DC voltage of the battery into alternating voltage of a sinusoidal shape of a standard frequency and voltage.
The electricity accumulated in the battery through the inverter in the form of an alternating current of a sinusoidal shape of a standard frequency and voltage is supplied to the consumer.

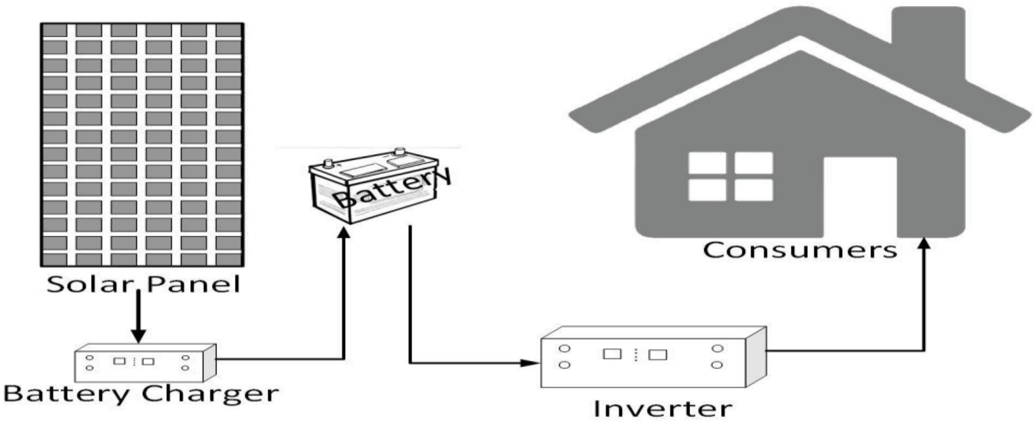


*Figure 2-14 The structure of off-grid photovoltaic power plant*

There are various types of batteries, respectively, their parameters and characteristics of the processes of charge and discharge are different. The most common types of batteries are listed below, their parameters and characteristics are given in **Table 2.6**. Those batteries can be used in solar power plants.

*Table 2-6 The Comparative characteristics of the most commonly used types of batteries*

| **Parameters** | **Lead acid** | **Nickel Cadmium (NiCd)** | **Nickel Metal Hydride (NiMH)** | **Lithium-ion (Li ion)** |
|---|---|---|---|---|
| Specific energy consumption, kW·h | 30-50 | 45-80 | 60-120 | 90-190 |
| Life cycle (80 %) discharge | 200-300 | 1000 | 300-500 | 500-2000 |
| Fast charge time | 8-16 hours | 1 hour | 2-4 hours | 1 hour |
| Overcharge Tolerance | High | Medium | Low | It does not allow constant recharging |
| Self-discharge / month (at normal temperature) | 5% | 20% | 30% | Less than 10% |
| Voltage in the cell (nominal), V | 2 | 1.2 | 1.2 | 3.3-3.8 |
| Peak Load Current* | 5 C | 20 C | 5 C | >30 C |
| Charging temperature | From -20°C up to 50°C | From 0°C up to 45°C | From 0°C up to 45°C | From 0°C up to 45°C |
| Discharging temperature | From -20°C up to 50°C | From 0°C up to 65°C | From 0°C up to 60°C | From 0°C up to 60°C |

| | | | | |
|---|---|---|---|---|
| Service requirements | 3-6 months (charging) | 30-60 days (discharging) | 30-90(discharging) | Not required |
| Security requirements | thermally stable | thermally stable | thermally stable | Mandatory protective circuit |
| Is used from | Late 1800 | 1950 | 1990 | 1991-1999 |
| Peak Load Current* | 5 C | 20 C | 5 C | >30 C |

**Battery Charge Controller:**

In solar power plants, charge controllers are used to charge, control and protect batteries
The charging controller automatically controls the charging modes, discharge and load of the battery from the solar panel, ensures safe and maximum charge of the batteries, protects the battery from overcharging and over discharge, stabilizes the incoming voltage and cuts off power when charging is completed, helps increase battery life, protects the battery from overloads and short circuits.

**Figure 2.15**: shows an approximate charge characteristic of a lithium-ion battery.

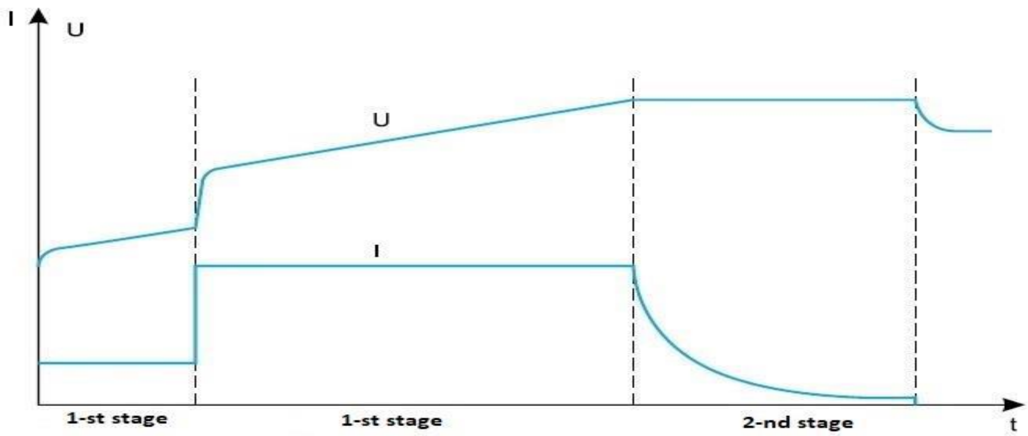


*Figure 2-15 Lithium-ion battery charge characteristic*

The battery is charged with maximum current, i.e. receives all current generated by the solar panel. When the charge is completed, the controller automatically maintains voltage at a certain level, which helps prevent overheating and gas formation in the battery. As the battery charges, the charge current gradually decreases.

**load current relative to capacity C in Ah**

Charging the battery is possible if the voltage at the output of the charger is higher than the voltage of the battery. Only in this case, the flow and regulation of the charging current is possible. In case of a solar power plant, when the solar panel is the source of charging current, charging the battery is possible in conditions of intense solar radiation, when the voltage of the solar panel is high enough, and the battery is in a significantly discharged mode - to such an extent that the battery voltage is lower than the voltage of the solar panel. In this case, a "transformerless" charger is used.

However, there may be cases when the battery requires recharging, and solar radiation is not intense enough and the voltage of the solar panel is not enough to overcome the threshold for the flow of charging current. The potential energy of the solar panel is still sufficient to charge the battery, but charging is not possible due to the low voltage of the solar panel (relative to the battery). In such cases, transformer chargers are used that are able to increase the voltage at the output of the charger to the necessary extent. Such chargers are made according to the "DC transformer" scheme: inverter - transformer - rectifier with subsequent monitoring and regulation of the charging current in the above manner.

***Objectives:***

- Study of the operation and characteristics of a solar photovoltaic power plant in battery charging mode supplying a load.

***Experiment Components:***

- **Sunlight Control (PV Panel Module)** – the user can control the sunlight intensity which is measured in %.
- **PV Panel Position Control** - the user can move the position of the PV Panel pressing the respective arrows
- **Sun Simulator Position Control** - the user can move the position of the Sun Simulator pressing the respective arrows

**Control and Measurement Module block includes**:

- **Voltage (PV Panel, Charge Controller)** – shows the voltage value of the PV Panel/Charge Controller
- **Current (PV Panel, Charge Controller)** – shows the current value of the PV Panel/Charge Controller
- **Power (PV Panel, Charge Controller)** – shows the power value of the PV Panel/Charge Controller
- **Sensor (Solar Irradiation)** - shows the solar irradiation generated by the solar simulator

**CMM Overcurrent** – indicates whether there is an overcurrent in the CMM's section. In case of overcurrent, the indicator lights up to orange.
**Overcurrent Reset** – resets the overcurrent. It is used when the 'CMM overcurrent' indication is orange.

## Application Software Description :

**Figure 2.16** shows the screenshot of Lab 4.

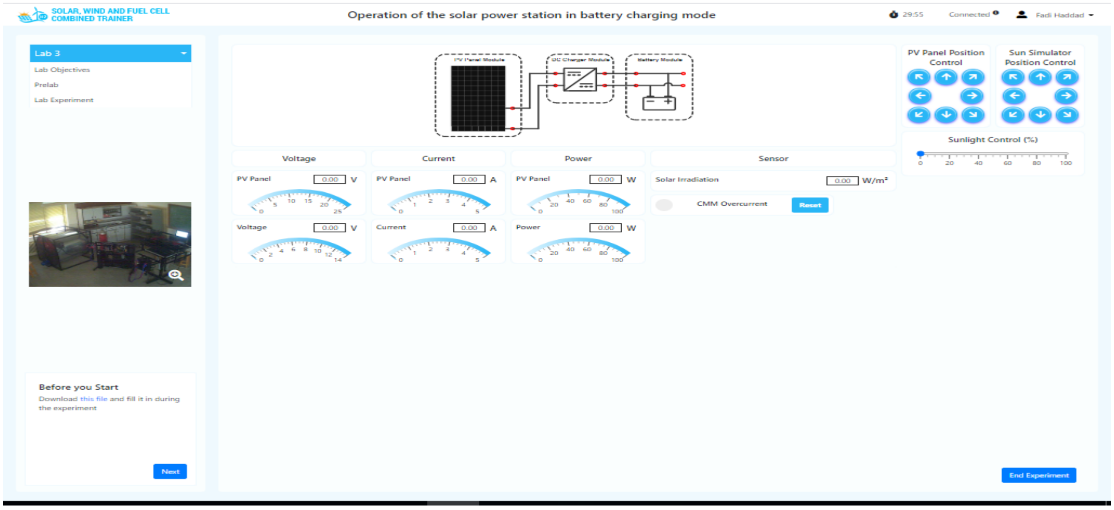


*Figure 2-16 Screenshot of Lab 4*

## Step by Step Instructions*:*

1. Open Lab 3 in the software

2. Move the *array of halogen lamps* to a position perpendicular to the PV panel in both X and Y axes using the PV Position Control and the Sun Simulator Position Control from the software.

3. Set the Sunlight Control (%) to 0% from the software.
The tests are implemented with the following sequence.
The battery charging characteristic is the dependency of battery voltage and current from the applied solar irradiation.
The dependency is determined the following way.
4. Gradually and smoothly increase the Sunlight Control (%) from the software and fix it in several positions. At each position determine the following:
- Solar Irradiation
- PV Panel Voltage,
- Charge Controller Current,
- Charge Controller Power

5. Determine the Solar Irradiation, PV Panel Voltage and the Battery Voltage at the moment when the battery stops charging (as it is completely charged).

6. Save the results in **Table 2.7**

7. After completing the test turn set the Sunlight Control (%) to 0%.

*Table 2-7 Battery Characteristics*

| | | | | | |
|---|---|---|---|---|---|
| **Solar irradiation S, W/m2** | | | | | |
| **PV panel voltage Up, V** | | | | | |
| **Battery voltage of the Ua, V** | | | | | |
| **Charge controller current I, A** | | | | | |
| **Charge controller power P, Watt** | | | | | |

## Experiments:

According to the measurements set forth in Table 2-2, build a characteristic of the battery charge: a graphical dependence of the Charge controller Current and Charge Controller Power on the PV Panel Voltageat these initial values, the battery voltage before charging

$$I, P = f(Up) \text{ where } Ua_o = const$$

## Questions:

1- Which types of batteries have the largest capacity?

a. Lead acid

b. Nickel cadmium

c. Lithium ion

2. What voltage does the battery charge?

a. Alternating (AC)

b. Direct Current (DC) with the polarity (+ of supply with + of the battery, – with the –)

c. Direct Current (DC) with the polarity (+ of supply with - of the battery, - with the +)

3. When the voltage of the PV panel increases, the battery charge current:

a. Increases

b. Decreases

c. Remains unchanged

4. As the battery charges, the charge current:

a. Increases

b. Decreases

c. Remains unchanged

5. What is the meaning of pulse width modulation of the charge current?

### Instructions for Preparation of Lab Report

Before preparing your report, complete the tasks and answer questions throughout the lab sheet.

YOUR Report must include:

- Introduction: A brief about the experiment
- Material and Methods/ Procedure
- Analysis
- Results and Discussion
- Conclusion

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# *Power Generation Trainer Lab Sheets*

## *Exp No.5 Solar Power Trainer: Autonomous Operation of a Solar Power Plant Supplying a load*


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*Firas Al-Adayleh*
*Reviewed by: Ziyad Altarwaneh*
*Khaled Alawasa*
*Saud Althunibat*

## 2.5 Experiment No. 5 Autonomous operation of a solar power plant supplying a load

### Introduction:

The solar power plant can operate in battery charging mode supplying a load. In this case, the electrical energy generated by the power plant is used to power autonomous consumers not connected to the grid. The power consumption is always equal to the power generated by the power plant. (The power losses in the electrical equipment and cable connections are related to power consumption.)

The power consumption is arbitrary – it is determined by the number and power of the connected consumers; the power that a solar power plant can generate is determined by the intensity of solar radiation - this power depends on external conditions and is practically unregulated. Therefore, there is always an inconsistency between the required power consumption and the possible power generation. Usually, at daytime, the power of the possible generation is greater than the power of consumption; in twilight or at night, the power of generation is small or equal to zero, and the power of consumption, on the contrary, increases. In such conditions, the use of a solar power plant to power autonomous consumers is possible only for a short time with low efficiency and is practically excluded.

The way out of this situation and the real possibility of using a solar power plant to power autonomous consumers is to use an electric energy accumulator. An electric battery is connected at the output of the solar panels via a charge controller. The battery is an additional power consumer in the power plant at daytime, when there is an excess of generating power relative to the power consumption – in this case the battery is intensively charged and accumulates electricity; at the same time, the generation efficiency increases. In the twilight or at night, when there is a lack of generation power relative to the consumption power, the battery feeds the consumers with accumulated electric energy through the existing inverter.

The power plant consists of a solar module (photoconversion panel), a battery, a battery charger, an inverter. The inverter output is connected to a consumer of electrical energy.
The elements of the power plant, perform the following functions.

The solar panel converts the energy of solar radiation directly into direct current electrical energy.
The battery is charged by the current generated by the solar photo converting panel through the charger and accumulates electrical energy.
The battery charger automatically adjusts the charging current of the battery depending on the type of battery, the degree of charge of the battery, its voltage and the voltage on the solar panel.
The inverter converts the DC voltage of the battery into alternating voltage of a sinusoidal shape of a standard frequency and voltage.

The electrical energy accumulated in the battery through the inverter in the form of an alternating current of a sinusoidal shape of standard frequency and voltage is supplied to the consumer.

Depending on the presence or absence of solar radiation, the degree of its intensity and the load of consumers, the battery operates either in charge mode, or in discharge mode, or in buffer mode; in the latter case, the battery is simultaneously charged and feeds the load.

The charging mode of the battery was investigated in Lab 3. In all cases, the consumers are powered by the battery through the inverter.

**The inverter performs the following functions**:

- converts DC voltage to AC voltage;
- coordinates the voltage levels at the input and output of the inverter, i.e. coordinates the battery voltage with the consumer voltage; the voltage coordination is carried out by means of a transformer, which is part of the inverter
- if necessary, stabilizes the voltage at its output (at the input of consumers) when the voltage at the inverter input (battery voltage) changes over a wide range - practically from + 20% to - 30% of the nominal value of the battery voltage, as well as when changing the magnitude and nature of the load within from idle to nominal,
- stabilizes the frequency of the output voltage,

  provides a sinusoidal (or close to it) shape of the output voltage.

The voltage inversion, i.e. the conversion of direct current voltage (DC) to alternating current voltage (AC) is performed by a voltage inverter. The circuit of a single-phase voltage inverter is shown in **Figure 2.17.**

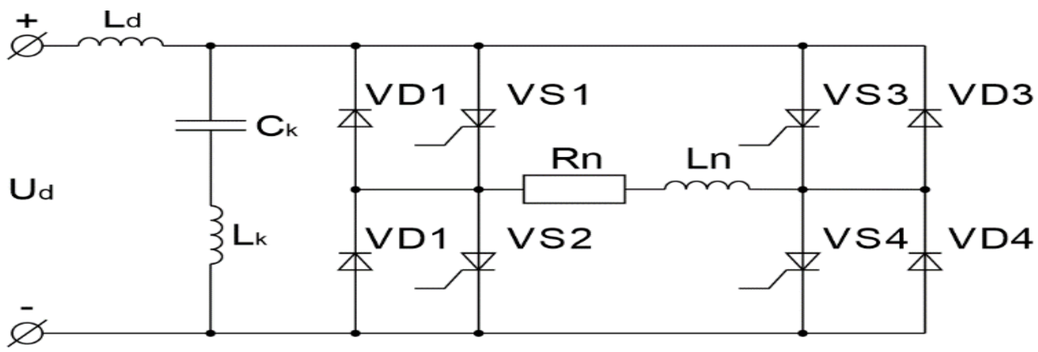



*Figure 2-17 The circuit of a single-phase voltage inverter*

The inverter consists of two pairs of switching thyristors VS1, VS4 and VS3, VS2, two pairs of reverse diodes VD1, VD4 and VD3, VD2, a resonant circuit consisting of a capacitor CC and an inductance LC; the inverter is connected to the AC active-inductive load RL - LL (in the general case).

The conversion of direct voltage (DC) to alternating current (AC) is performed as follows and is illustrated in the graph in **Figure 2.18**.

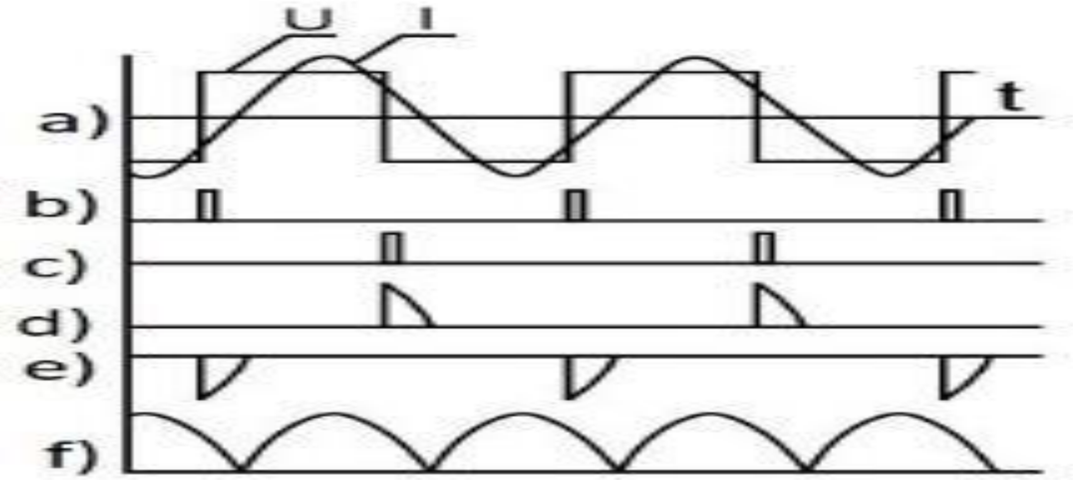



*Figure 2-18 Inverter voltage and current diagram a) the voltage U and current I (first harmonic) on the load, b) switching thyristor pulses VS1, VS4, c) switching thyristor pulses VS3, VS2, d) current in the circuit of reverse diodes VD3, VD2.*

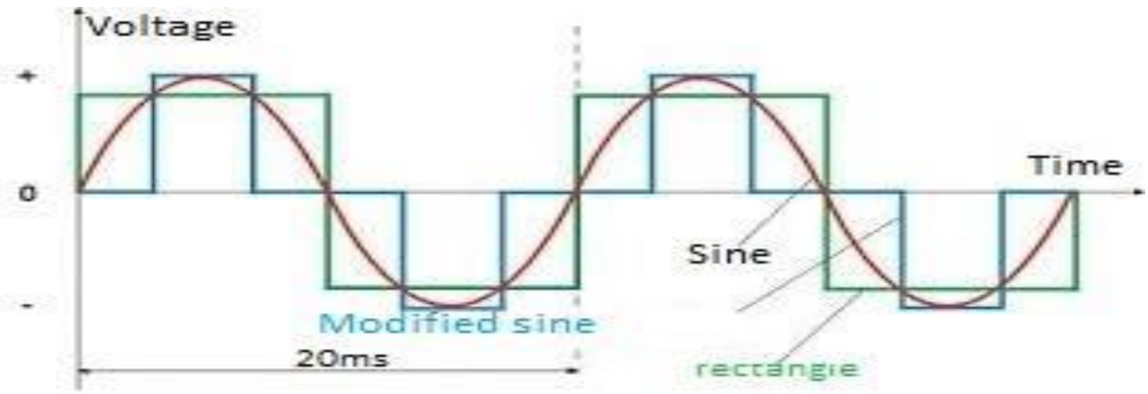



*Figure 2-19 Diagram of obtaining a modified inverter voltage sine by means of a single pulse-width modulation.*

***Objectives:***

- Study of the operation and characteristics of a solar photovoltaic power plant operating off-grid supplying a load without connecting to the grid

- Study of the methods and the devices for regulating the frequency and the voltage

***Experiment Components:***

- **Sunlight Control (PV Panel Module)** – the user can control the sunlight intensity which is measured in %.
- **PV Panel Position Control** - the user can move the position of the PV Panel pressing the respective arrows
- **Sun Simulator Position Control** - the user can move the position of the Sun Simulator pressing the respective arrows

- **AC/DC Transformer Module** - this object provides ON and OFF indications of the module. In addition, it has an Enable Module checkbox, which helps to remotely allow the control of the module on the trainer.
- **RLC Load Module includes:**
  SR1, SR2, SR3 switches – switches ON and OFF each stage of the Resistive load
  SL1, SL2, SL3 switches – switches ON and OFF each stage of the Inductive load
  SC1, SC2, SC3 switches - switches ON and OFF each stage of the Capacitive load

**Control and Measurement Module block includes**:

- **Voltage (PV Panel, Charge Controller)** – shows the voltage value of the PV Panel/Charge Controller
- **Current (PV Panel, Charge Controller)** – shows the current value of the PV Panel/Charge Controller
- **Power (PV Panel, Charge Controller)** – shows the power value of the PV Panel/Charge Controller
- **Sensor (Solar Irradiation)** - shows the solar irradiation generated by the solar simulator
- **CMM Overcurrent** – indicates whether there is an overcurrent in the CMM's section. In case of overcurrent, the indicator lights up to orange.
- **Voltage THD, Current THD (%)** - shows the total harmonic distortion values for voltage and current respectively, per phase

- **Overcurrent Reset** – resets the overcurrent. It is used when the 'CMM overcurrent' indication is orange.

### Application Software Description :

Below (**Figure 2.20**) is the screenshot of Lab 4> System layout tab

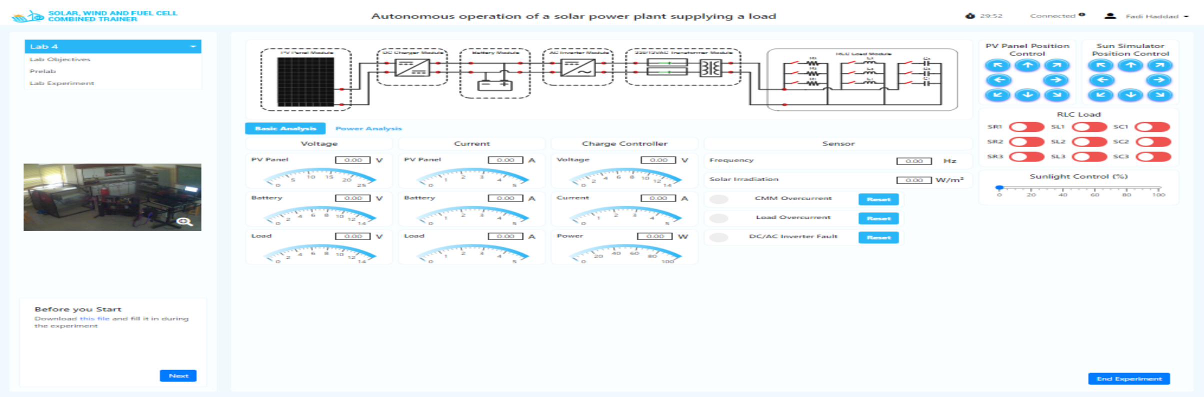



*Figure 2-20 Screenshot of the lab*

### Step by Step Instructions:

The experiment is carried out in the following sequence of actions:

***Please note that in this lab the Battery module is used as a power source. In case the battery voltage is below the minimum limit, a pop up (Figure 2.21) will appear in the software to prompt you to charge the battery.***

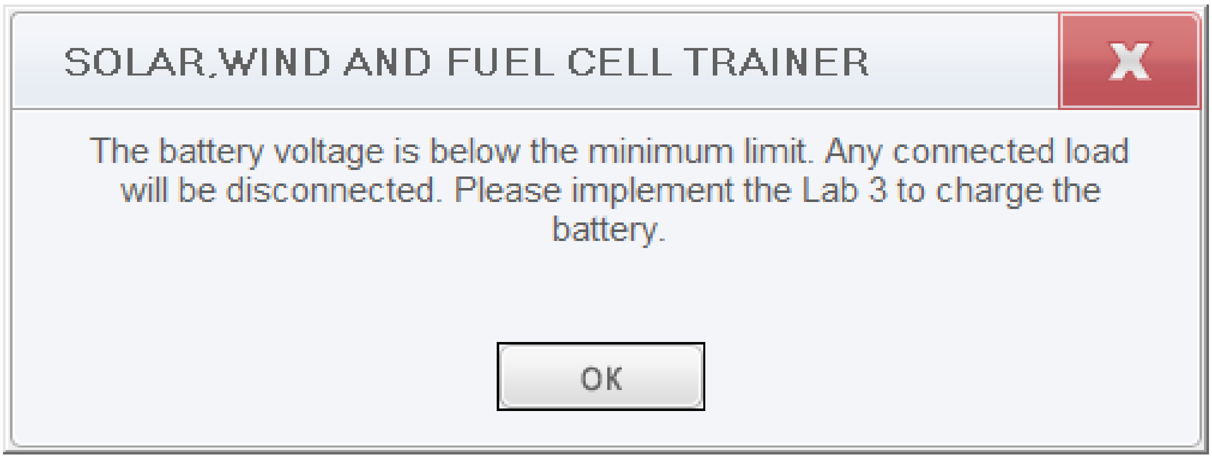



*Figure 2-21 A message for the lowe level of the battery*

1. Open Lab 4 in the software

In this experiment, the external characteristics and the accuracy of stabilizing the voltage and frequency of the alternating current at the load will be determined in the case when the load and irradiation change. The accuracy of voltage and frequency stabilization is calculated based on external characteristics.

The external characteristic is the dependence of the voltage and frequency of the alternating current on the load when changing the resistive, resistive-inductive and active-capacitive load ranging from idle to approximately nominal at a certain illumination.

External characteristics are determined when the circuit is powered by a battery operating in buffer mode with the solar panel (i.e., when the battery is recharged from the solar panel) under different lighting conditions, with the current state of charge of the battery and, accordingly, the voltage of the battery.

The characteristic is determined at a fixed position of the panel, in which the light flux of the simulator is directed perpendicular to the surface of the panel.

2. Move the *array of halogen lamps* to a position perpendicular to the PV panel in both X and Y axes using the PV Panel Position Control and the Sun Simulator Position Control from the software. The experiment is implemented in the following sequence.

External characteristics are determined as follows.

3. Set the Sunlight Control to 0%.

4. Check the Enable Module checkbox on the Transformer Module, and turn it on by pressing the Remote Start button.

5. External characteristics are determined at various fixed irradiation values - from zero to the nominal, and with several intermediate irradiation values. Gradually and smoothly increase the

Sunlight Control from the software and fix it in several positions. In each position determine the irradiation and the external characteristics as per the points below:

6. At each position of irradiation, set three values of the resistive load - ranging from idle to nominal. For each value of the resistive load, turn on an inductance or a capacitance, depending on the characteristic being determined. By switching the SR switches of the RLC Load Module (respectively, the resistive current), set the value of the power factor close to *cos φ = 0.8* (for a resistive -inductive load) or *cos φ = - 0.8* (for a resistive -capacitive load)
7. At each position of the Solar Irradiation and for each value of the resistive load, measure the following parameters:
- Solar Irradiation,
- PV Panel Voltage,
- Charge Controller Current,
- Charge controller Power,
- Battery Voltage,
- Load Voltage
- Load Current,
- Load Power,
- Load Active Power,

8. Save the results in **Table 2.8** up to **Table 2.9**

9. After completing the tests set the Sunlight Control to 0%.

*Table 2-8 Load characteristics in case of S = 0 (irradiation of the panel)*

| | | | | |
|---|---|---|---|---|
| Solar Irradiation *S* | | | | |
| Load type | Resistive ,<br>Resistive -Inductive load<br>Resistive -Capacitive load | | | |
| Load steps | 0 | 1 | 2 | 3 |
| PV panel voltage *Up* | | | | |
| Charge controller current *Ib* | | | | |
| Charge controller power P*b* | | | | |
| Battery voltage *Ub* | | | | |
| Load voltage *U* | | | | |
| Load current *I* | | | | |
| Load active power *P* | | | | |
| Load power factor *cos φ* | | | | |

*Table 2-9 Loading characteristic when irradiation S =……….*

| | | | | |
|---|---|---|---|---|
| Solar Irradiation *S* | | | | |
| Load type | Resistive ,<br>Resistive -Inductive load<br>Resistive -Capacitive load | | | |
| Load steps | 0 | 1 | 2 | 3 |
| PV panel voltage *Up* | | | | |
| Charge controller current *Ib* | | | | |
| Charge controller power P*b* | | | | |
| Battery voltage *Ub* | | | | |
| Load voltage *U* | | | | |
| Load current *I* | | | | |
| Load active power *P* | | | | |
| Load power factor *cos φ* | | | | |

## Experiments:

Insert the measurements in the Table 2.8 up to Table 2.9
Insert the data of the experiment in Table 1.3-1 in case of no Solar Irradiation *S = 0* (The solar panel is not illuminated), insert the data of the experiment in Table 1.3-2 in case of nominal irradiation *S = Snom,* insert the data of the experiment in Table 1.3-1, Table 1.3-2 in case of intermediate irradiation values.

The power factor is determined by software or based on the measured values as follows.

$$\cos\varphi = P / S = P / U I. \qquad (1)$$

Build external characteristics: graphical dependence of the voltage on the load on the load current and active power at a given power factor:

$$U = F(I, P), \text{ in case } \cos\varphi = 1, \cos\varphi = 0{,}8, \cos\varphi = -0{,}8 \text{ in case } S = const. \qquad (2)$$

Determine the accuracy of maintaining voltage on the load and on the battery

$$\Delta U = \pm [(U_{max} - U_{min}) / 2], \qquad (3)$$

$$\Delta U_a = \pm [(U_{a\,max} - U_{a\,min}) / 2]. \qquad (4)$$

## Questions:

1. Load voltage stability…

    a. depends on the irradiation directly

    b. is inversely dependent on irradiation

    c. doesn't depend on the irradiation

2. The stability of the voltage frequency at the load depends on:

    a. The irradiation

    b. The battery voltage

    c. The control system of the inverter

3. With an increase in the inductive component of the load, the shape of the voltage curve:

    a. Approaches sinusoidal

    b. Deviates from sinusoidal

    c. Remains unchanged

4. Electricity consumed by the consumer for 1 hour at twilight hours of the day, how does it compare with the amount of energy produced by PV panels for the same hour (excluding losses)?

    a. consumed energy should be equal to produced

    b. consumed energy should be less than produced

    c. consumed energy can be more than produced

**Instructions for Preparation of Lab Report**

Before preparing your report, complete the tasks and answer questions throughout the lab sheet.

YOUR Report must include:

- Introduction: A brief about the experiment
- Material and Methods/ Procedure
- Analysis
- Results and Discussion
- Conclusion

Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

Co-funded by the Erasmus+ Programme of the European Union

# *Power Generation Trainer Lab Sheets*

## *Exp No. 6 Wind Power Trainer: Wind Turbines and Wind Power Plants*

*A-structure and characteristics of wind turbines and wind power plants.*
*B-structure and characteristics of wind generators used in wind power plants.*


*Prepared by: Walaa Al Saraireh*
*Firas Al-Adayleh*
*Reviewed by: Ziyad Altarawneh*
*Khaled Alawasa*
*Saud Althunibat*

## 2.6 Experiment No. 6 Structure and characteristics of wind turbines and wind power plants

**Introduction*:***
The wind power plant is a device for converting the mechanical energy of the air flow (wind) into electrical energy.

The wind power plant consists of a Wind Turbine-Generator set, which in turn consists of a wind turbine, an electric generator connected to it and devices for connecting the turbine and generator, as well as additional measuring and regulating devices.

The Wind Turbine-Generator set generates the electric power in accordance with the power of the air flow (wind), which, in its turn, depends on the air flow speed. The air flow speed (wind) varies widely, depending on the natural conditions, at certain intervals of time the wind may not be at all. Consequently, the generated electric power also has a variable character: there are certain intervals of time when there is no generation of electric power at all.
The wind power plants, according to the method of using the electrical energy, are divided into the following types:
1. The on-grid wind power plants
2. The off-grid wind power plants in battery charging mode

The on-grid wind power plants, being connected to the grid, have the voltage and frequency of the grid, regardless of the air flow speed (wind) and the generated electrical power. There are no devices for regulating the voltage and the frequency. All the electric power generated by the wind power plant is transferred to the power grid. There are no energy storage devices. In this case, the wind power plant consists of a wind-turbine generator set as well as switching and measuring devices.

In case of using the regulated generators, it is possible to regulate the excitation current of the generators by means of the corresponding devices with the purpose to regulate the reactive current of the generator. The on-grid wind power plants are being usually powerful industrial power plants. At the same time, those wind power plants are connected to the wind farms where there is a large number of similar wind farms, each of which is connected to the grid directly or through a grid that unites them. The off-grid wind power plants in battery charging mode supply the stand-alone load, providing a stable frequency and voltage, regardless of wind, its speed and the magnitude and characteristics of the load. To meet those requirements, a battery, a charger, a ballast load, an inverter that converts the DC voltage into AC, switching devices, control and measurement devices are used in the wind power plant The off-grid wind power plants in battery charging mode are usually designed for individual use and for supplying the stand-alone objects - a country house or small farm.

**The Design of the wind turbines**

The wind turbine - is an air engine that converts the mechanical energy of the air flow (wind) into the energy of the rotating shaft.

The blade rotary impeller is the main operating element of the wind turbine in which the energy is converted. The shaft of the wind turbine (impeller) is connected to the shaft of the electric generator directly or via a reducer. There are as well other types of connections of the turbine and the generator. The combination of a wind turbine and an electric generator is considered to be a wind power plant. The power of the modern wind generators can reach up to 8 - 15 MW per unit.

The power generated with the Wind Turbine-Generator set depends on the power of the air flow (wind) which is expressed by the air flow speed (wind) and the surface covered by the blades of the rotary impeller of the turbine:

$$P=pSV\text{^}3=p(\pi D\text{^}2/4)\ V\text{^}3$$

where $p$=1.25 [kg/m2] - the density of air, $S$=$\pi D$2/4 - the surface covered by the blades of the turbine rotor [m2], $D$- diameter of the impeller [m], $V$- airflow speed (wind) [m/s].
There are two main types of the wind turbines: with a horizontal axis of rotation and with a vertical axis of rotation. In both types of the turbines there is a lift effect. The lift vector directed perpendicular to the axis of rotation creates a torque that is applied to the shaft and drives the rotor of the generator and generates electric power. The wind power factor of an ideal wind wheel of horizontal, propeller and vertical-axis wind generators is equal to 0.593. By now, the achieved wind power factor on the horizontal and propeller wind generators, is equal to 0.4

**1. The wind generators with wind turbines with a horizontal axis of rotation**

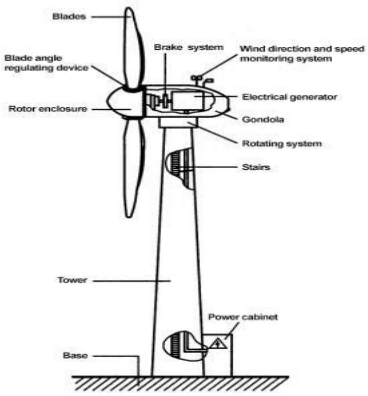



*Figure 2-22 The design of the horizontal axis wind turbine*

*Figure 2-23 The general view of the offshore horizontal axis wind turbine*

The wind generators (propeller type) have several blades with the possibilities of changing the angle of attack of the blades in the direction of the wind, the yaw mechanism in wind turbine responsible for the orientation of the wind turbine rotor towards the wind, a reducer for matching the rotational speed of the turbine with the generator and other devices as shown in Figure 2.0-1.

***Advantages****:* the maximum power per unit in comparison with other types of wind power generators, reaching 3 to 8 MW per unit; it can be developed up to 15 MW.

***Disadvantages:***

• The large mass-dimensions of the propeller turbine wheel, diameter of which for certain power reaches several tens of meters

• a low rotational speed, which necessitates the use of reducers for articulation with the generator, and leads to an increase in the mass of the wind turbine and the complication of its design

• even the achieved capacities of up to 3-15 MW per unit are incomparably small compared to the capacities of power units of hydraulic and thermal power plants, capacities that reach several hundred and more MW per unit; this fact forces for the use of wind power generators on an industrial scale in power systems to create wind farms with a large number of wind power generators reaching several hundred and thousands of units in the zone of the airflow - this significantly increases capital expense and operating costs and increases alienated territories

• high level of low-frequency noise, which adversely affects humans and animals

**2. The wind generators with wind turbines with a vertical axis of rotation**

Orthogonal vertical-axial wind generators have a vertical axis of rotation and several blades parallel to it, in a certain distance. The position and operation of those wind generators do not depend on the wind direction. Those wind generators begin to generate energy at a wind speed of 0.7 m/sec.

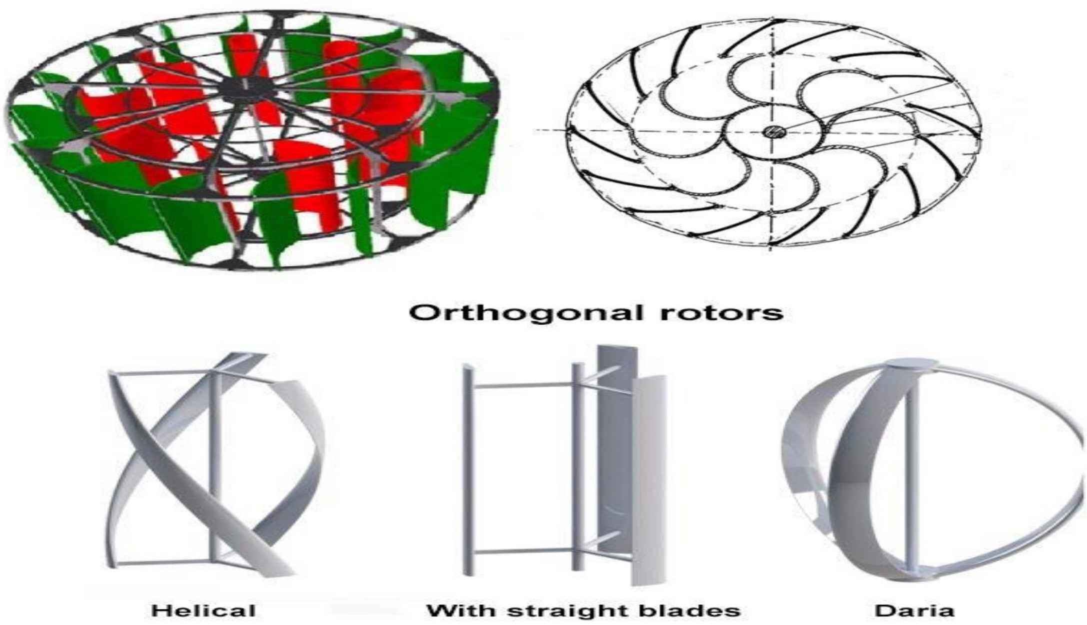



*Figure 2-24 Wind turbine with multi-blade rotor*

***Advantages**:*

• possibility to use even in weak winds,

• no need to use guiding mechanisms (except the wind generators with a multi-bladed rotor with a guiding device)

• wind generators can be located at ground level, which greatly simplifies its operation,

• low noise level

***Disadvantages**:*

- lower service life of the support nodes, due to higher dynamic loads on them from the rotor side, because when the rotor rotates, the lift force from each blade changes its direction by 360 °, which creates additional dynamic loads,

• the blade system of the orthogonal installations is more massive compared with its equivalents on capacity, the horizontal-axial installations

• The coefficient of efficiency is lower compared with horizontal-axial, since during one rotation of the rotor, the angles of attack of the wind flow on the blade vary widely, while in horizontal wind generators they can be set close to optimal.

## B-*STRUCTURE AND CHARACTERISTICS OF WIND GENERATORS USED IN WIND POWER PLANTS*

The electrical generators convert the mechanical energy of rotation into electrical energy. In the wind power plants, the generators are driven by wind turbines. The design and characteristics of wind turbines and wind power plants are described and studied in Lab 1. The types of electric generators used in wind power plants, their design and characteristics depend on the operation mode of the wind power plant.

The wind generators, according to the method of using the electrical energy, are divided into the following types:

1. The on-grid wind power generators

2. The off-grid wind power generators in battery charging mode

The on-grid wind power generators, being connected to the grid, have the voltage and frequency of the grid, regardless of the air flow speed (wind) and the generated electrical power. The rotational speed of the generator, accordingly, of the wind power plant, is constant - it depends only on the frequency of grid. There are no devices for regulating the voltage and the frequency. All the electric power generated by the wind power plant is transferred to the power grid.

In case of using the regulated generators, it is possible to regulate the excitation current of the generators by means of the corresponding devices in order to regulate the reactive current of the generator.

The on-grid wind power plants are being usually powerful industrial power plants.

The off-grid wind power plants in battery charging mode supply the stand-alone load, providing a stable frequency and voltage, regardless of wind, its speed and the magnitude and characteristics of the load. To meet those requirements, a battery, a charger, a ballast load, an inverter that converts the DC voltage into AC, switching devices, control and measurement devices are used in the wind power plant. This kind of operation mode is investigated in a detailed way in Lab 6.

The off-grid wind power plants in battery charging mode are usually designed for individual use and for supplying the autonomous objects - a country house or small farm.

**Table 2.0- 1** shows the operation modes of wind power plants and the types of the used electric generators and their corresponding characteristics.

**Table 2.0-1: Operation modes of the wind power plants and the types of the used electric generators:**

| Operation modes of the wind power plants and the generator | Methods for stabilizing the frequency and the voltage | The characteristics of the generators | The type of the generator |
|---|---|---|---|
| On-grid mode | The stability of the frequency and the voltage is provided with the grid. | The reactive current of the generator is not regulated. | 1.Synchronous generator with permanent magnets with unregulated excitation 2. Asynchronous generator with squirrel-cage rotor |
| | | The reactive current of the generator is regulated. | The synchronous generator with excitation coil (with regulated excitation). |
| Off-grid mode | The stability of the frequency and the voltage is provided with the battery and the inverter. The wind | The active and reactive current of the generator is determined by the stand-alone load | The synchronous generator with permanent magnets (with unregulated excitation). |

| | | | |
|---|---|---|---|
| | power plant is unregulated. | connected to the generator. | |
| | The stability of the frequency and the voltage is provided by the generator in case of the variable speed rotation. | The active and reactive current of the generator is determined by the autonomous load connected to the generator. | The Asynchronized synchronous generator. |

**Below you can find various types of electrical generators.**

## 1- Synchronous generator

### A- Operating principles of the synchronous generator

The electromagnetic circuit of the synchronous generator is illustrated in **Figure 2.25**

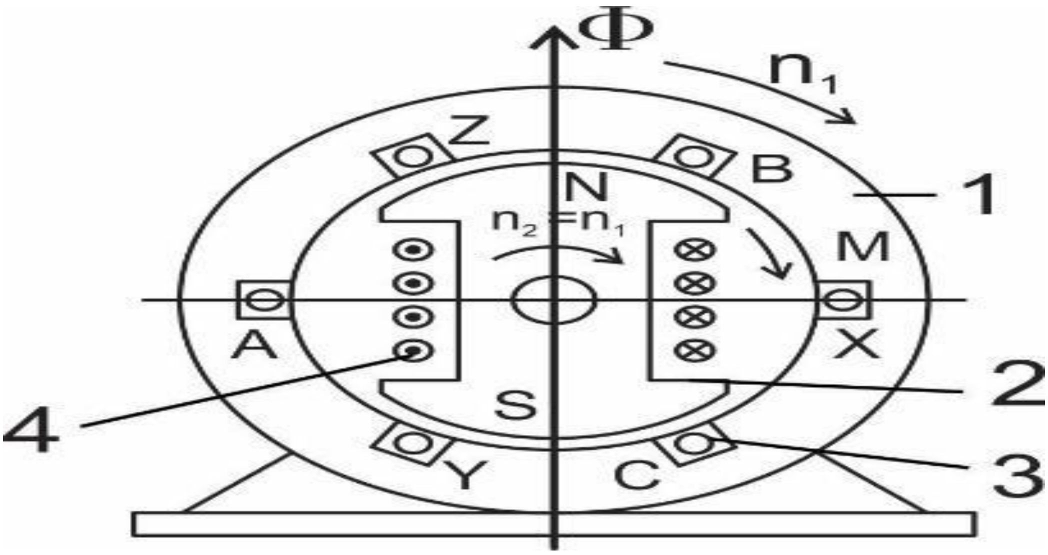



*Figure 2-25 The electromagnetic circuit of the synchronous generator 1 – stator, 2 – rotor, 3 – stator coil, 4 – excitation winding*

The electrical circuit of the synchronous generator is illustrated in **Figure 2.26**

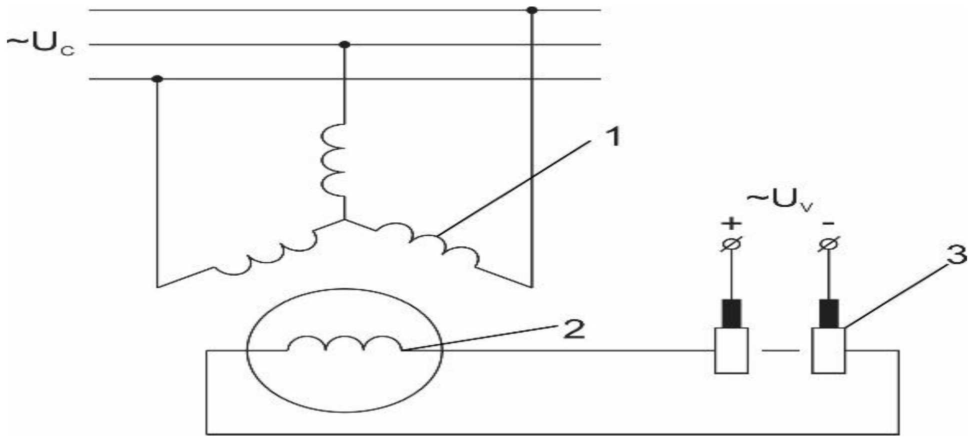



*Figure 2-26 The electrical circuit of the synchronous generator 1 –stator coil, 2 – excitation winding, 3 –brush contact assembly*

The synchronous generator consists of stator and rotor. The stator is represented as a hollow cylinder; the three-phase coil of AC is placed on its inner surface.

Inside the stator, there is a rotor with explicitly or implicitly expressed poles, on which the DC excitation coil is installed; it is the excitation winding of the rotor. Rotor coil is connected with regulated DC power supply, which creates regulated DC excitation in the rotor. The connection of the rotating excitation winding with DC power supply is implemented through the slip ring installed on the rotor and brush contacts implemented outside the rotor.
It is possible to transfer the excitation current to the rotating rotor from the stationary regulated power supply in a non-contact way by means of special devices, which are investigated below.

**b. Design of synchronous generators**
*Types of synchronous generators. Areas of usage.*
There are two fundamentally different constructions of rotors in the synchronous generators: salient pole rotor (see Figure 2.27a) and non-salient pole rotor (Figure2.27b).

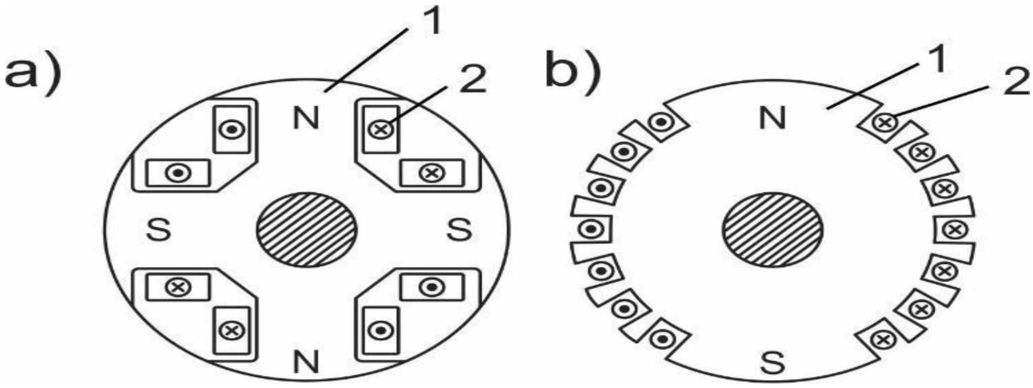



*Figure 2-27 a) Salient pole rotor generator and b) non-salient pole rotor generator 1 – rotor core, 2 – excitation winding*

The salient pole rotor is usually used in the generators with four or more poles ( $p$ = 2 or more). The excitation winding is carried out in this case in the form of coils of rectangular cross section, which are placed on the cores of poles and strengthened by means of pole pieces. The rotational speed of the salient-pole generators at a frequency of 60 Hz is from 1800 rpm and below - according to (Equation 1).

Non-salient-pole generators are used at two poles ($p = 1$). Those generators operate at the maximum possible rotation speed of 3600 rpm (at a frequency of 60 Hz) - according to (Equation 1). The rotational speed of the synchronous generator rotor at a given frequency of the generated voltage, according to (Equation 1), is strictly related to the number of pole pairs. The rotational speed and the number of poles of the rotor determine the structure of the rotor and the generator as a whole. The higher the rotational speed is, the smaller is the dimensions of the generator.
In the wind power plants, the shafts of the generator and the wind turbine are connected to each other directly (if they are designed for the same rotational speed), or by means of a reducer (if the rotational speeds of the turbine and the generator vary). The rotational speeds of the turbine and the generator are selected or projected depending on the minimum dimensions of the wind power plant or the minimum cost.

**c. Excitation systems of the synchronous generators**

The following two, fundamentally different excitation systems are used in the synchronous generators.

1) Regulated excitation system with excitation windings on the rotor and with a regulator of the excitation current.

2) Non-regulated excitation system with permanent magnets mounted at the poles of the rotor, without excitation windings and without an excitation regulator.

Excitation schemes of the synchronous generators with excitation windings on the rotor and with regulation of the excitation current are shown in **Figure2.28**. There are two types of systems depending on the supply method: the independent excitation and self-excitation.

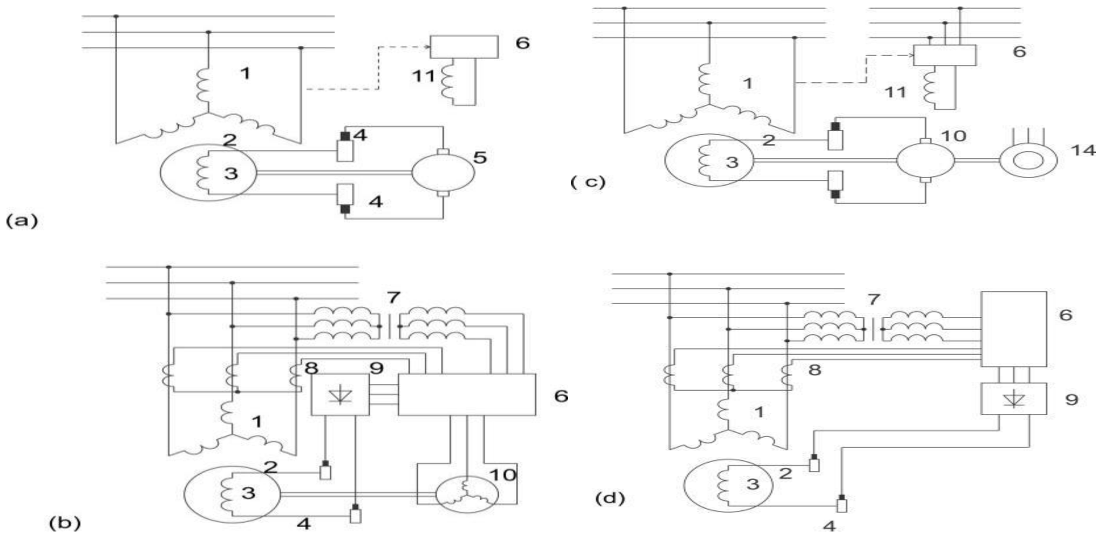



*Figure 2-28 a) Independent excitation of DC, b) independent excitation of AC c) independent excitation of auxiliary generator, d) self-excitation, e) brushless excitation system. (1 – stator winding of the generator 2 – rotor, 3 –excitation winding of the generator 4 – brush-contact assembly, 5 – DC exciter, 6 – excitation regulator, 7 – voltage transformer, 8 – current transformer, 9 – rectifier, 10 – dc exciter, 11 – excitation winding, 12 – rotating winding of ac exciter, 13 – rotating rectifier, 14 – auxiliary engine*

## 2.The Asynchronous generators

### a. The Design of the asynchronous generators:

The stator of a 3-phase asynchronous machine is arranged in a manner similar to the stator of a synchronous machine, a similar three-phase winding is placed on it, which is connected to a three-phase alternating current network. The rotor of an asynchronous machine is a cylindrical body assembled from electrical steel sheets with grooves for placing the winding. The most common are the asynchronous machines with a so-called squirrel-cage rotor. In those machines, the grooves are filled with an electrically conductive material - rods of copper or aluminum, the ends of which are connected by an electrically conductive ring. This design of the conductors is a short-circuited winding of the rotor.

With this design, the winding of the rotor, the asynchronous machine - unlike the synchronous machine - does not have a brush-and-pin assembly and an electrical connection with external electrical circuits. This ensures the simplicity of the design and the high reliability of the asynchronous machine. For this reason, the asynchronous motors operating in the propulsion mode - have become very popular. For the same reason, in some cases, at low power, the asynchronous machines are used as generators. Such kind of generators are called asynchronous generators.

**b. The operating principles and characteristics of an asynchronous machine**

The operation of the asynchronous machine is based on the principle of electromagnetic interaction between the rotating field, which is created by the 3-phase current system in the stator winding, and the current induced in the rotor winding when the conductors cross the rotating field. Thus, the operation of an asynchronous machine is similar to the operation of a transformer, and the stator can be considered as a primary winding, the rotor as a rotating secondary winding. The electromagnetic interaction between the stator and the rotor of the asynchronous machine is possible only with the difference between the speeds of the rotating stator field ($n_s$) and the mechanical rotation of the rotor ($n$), since at the rate of $n_s = n$, the stator field would be stationary relative to the rotor and in the rotor winding there would be no current.

Depending on the relationship between the speeds of the rotating stator field ($n_s$) and the mechanical rotation of the rotor ($n$), the operation of the asynchronous machine in engine, generator or electromagnetic brake modes is distinguished.

The dependence of the electromagnetic moment or electromagnetic power on the slip $S$, is determined by the rotation speed of the stator field ($n_s$) and the mechanical rotation of the rotor ($n$):

$$S = (n_s - n) / n_s$$

The rotation speed of the stator field ($n_s$), which is otherwise called the synchronous rotation speed, depends on the network frequency and the reduced number of pole pairs of the stator winding ($p$) and is determined by the following expression:

$$f = p\, n_s / 60 \;;\; n_s = 60\, f / p.$$

**c. Asynchronized synchronous generators**

The asynchronized synchronous generators are excited by AC. The 3-phase AC winding is installed on the rotor of the asynchronized in which an alternating 3-phase excitation current flows. The frequency of the excitation current and the magnitude of the current are regulated by an external driver (**see Figure 2.29**). The exciter is a frequency converter, at the output of which a 3-phase AC voltage with adjustable frequency is formed. The exciter power can be performed from an independent source of AC or DC or from the generator itself according to the self-excitation scheme.

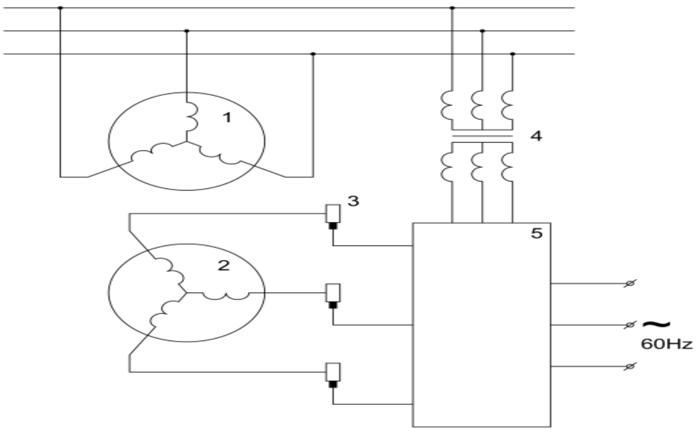



*Figure 2-29 Scheme of Asynchronized synchronous generators 1 – stator winding, 2 – generator excitation winding, 3 – commutator, 4 – voltage transformer, 5 – frequency converter*

The 3-phase AC excitation current generates a rotating excitation flux on the rotor surface, which rotates relative to the rotor surface at a rotational speed corresponding to the excitation current frequency. Those values are related by the equations:

$$f_g = p_g n_g / 60 \text{ [Hz], therefore } n_g = 60 f_g / p_g$$

where $p_g$ –the number of pole pairs of the excitation winding on the rotor, $n_g$ - the rotational speed of the excitation flux relative to the surface of the rotor [rpm], *60* - the matching factor between the frequency units [*Hz*] - [oscillations / second] and the rotor speed [rpm].

### 3. The advantages and disadvantages of the generators used in wind power plants

| Type of the generator | Advantages | Disadvantages |
|---|---|---|
| Synchronous generator with excitation winding (with regulated excitation) | 1. In case of on-grid operation, the reactive current and the power factor are being controlled.<br>2. In case of off-grid operation, the voltage stabilization is provided<br>3. High overload capacity and stability | 1. The existence of rotating excitation windings on the rotor.<br>2. The existence of a brush-contact assembly for transferring the excitation current to the rotor. |

| | | |
|---|---|---|
| Synchronous generator with permanent magnets (with non-regulated excitation) | 1. The absence of rotating excitation windings on the rotor.<br>2. The absence of a brush-contact assembly for transferring the excitation current to the rotor.<br>3. High reliability | 1. In case of on-grid operation, the inability to regulate the reactive current and the power factor.<br>2. In case of off-grid operation, the inability to stabilize the voltage |
| Asynchronous generator with a squirrel-cage rotor | 1. The absence of rotating coil windings on the rotor.<br>2. High reliability | 1. The ability to work almost exclusively in the on-grid mode<br>2. Large reactive currents<br>3. The inability of practically regulating the reactive current and the power factor |
| Asynchronous based synchronous generator | 1. The possibility of stabilizing the frequency of the generator voltage regardless of its rotational speed<br>2. High overload capacity and stability | 1. Complexity of design and large mass-dimensional characteristics. |

## 4. Synchronous generator of the Wind Power Generation Trainer

The synchronous generator of the trainer is a two-pole generator of an apparent pole structure (rotation speed -3600 rpm, linear voltage-12V, number of phases-3, frequency - 60 Hz, power – up to 250 W), specially designed for educational purposes. In a synchronous generator with permanent magnets, the excitation flux is constant and therefore the generator voltage is unregulated - it is determined only by the rotational speed of the generator and its load. On the trainer, the generated voltage can be regulated in magnitude by means of a Voltage Regulator Module which is installed outside the generator. The connection of the generator to the electrical network is performed through the Transformer Module Type 1 with voltages of 220/12 V.

The air flow speed and, accordingly, its power are determined by natural conditions - it varies arbitrarily and can't be regulated on the wind power. It is assumed that the wind power plant can operate and generate electricity at air flow speeds from a minimum speed of 3 m/s up to a nominal 10 m/s. Accordingly, the generated power can also vary from idle to nominal. But with all changes in the air flow speed, the nominal rotational speed of the generator is 3600 rpm, the rated voltage is 12 V, and the rated frequency is 60 Hz with allowable deviations. These requirements, depending on the mode in which the wind power plant operates, are provided in different ways.

### *Objectives*

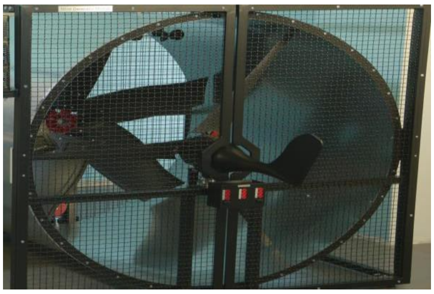
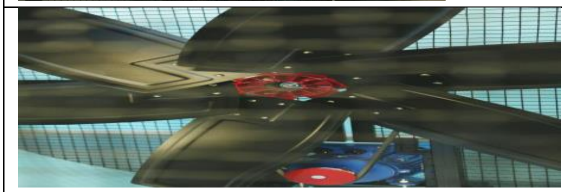
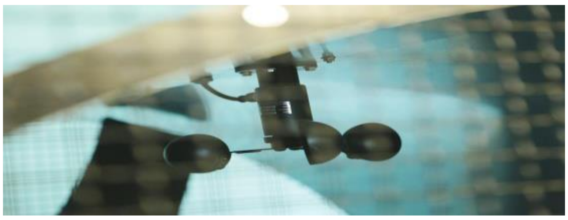
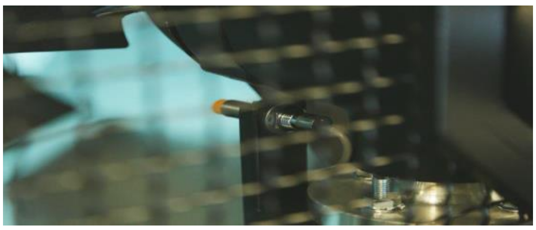
1) To get acquainted with various types of wind turbines and wind power plants

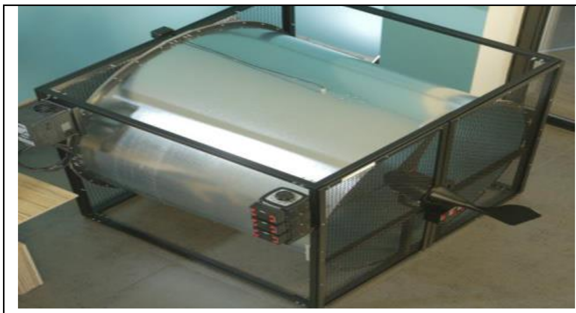
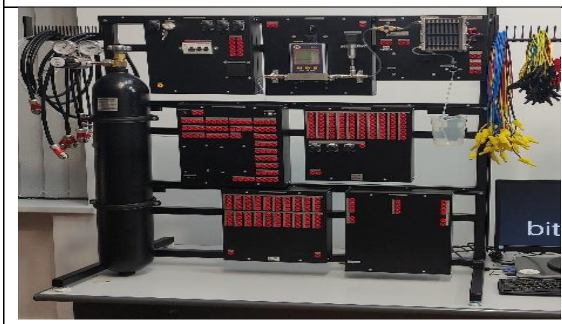
2) To study the wind turbine on the laboratory trainer
3) To study the wind generator on the laboratory trainer

### *Experiment Components:*

**Wind-Generator Module**

The Wind Generator Module consists of the following components:

| | |
|---|---|
|  | **Wind Turbine-Generator set**<br>*The Wind Turbine-Generator set* is intended for converting the mechanical energy into electrical energy. |
|  | **Wind Motor-Fan set**<br>*The Wind Motor-Fan set* is intended to emulate wind. The motor rotates the Fan with the V-Belt as a result of which the wind is emulated |
|  | **Wind speed sensor**<br>*The Wind speed sensor* measures the wind emulated in the wind tunnel. |
|  | **RPM for Fan (rotational speed sensor)**<br>*The RPM for Fan* measures the wind rotational speed. |

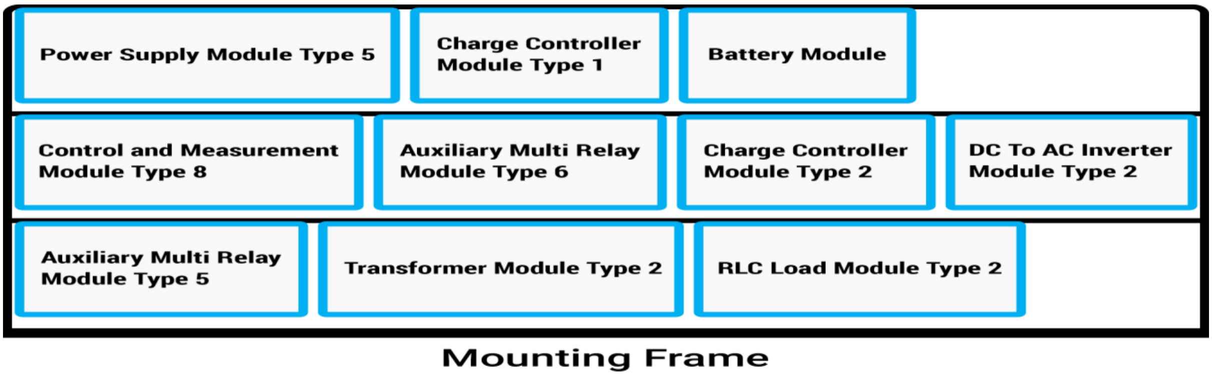
| | |
|---|---|
|  | **Wind Tunnel**<br>*The Wind Tunnel* is intended to direct the wind simulated by the Fan to the Wind Turbine-Generator set. |
|  | **VFD Block**<br>*The VFD Module* is intended to supply the Wind Motor. |
|  | **Mounting frame with components**<br>This is a metallic structure, intended to handle the components installed on it. The frame has front side and backside rails to handle the components for each lab which will give better view and understanding. |
|  | **Power Cables – one set**<br>Cable set includes cables with different lengths. The cables are used to wire system components. In order to simplify visual inspection of the wiring, cables have different colours with different collared plugs. |

### *Step by Step Instructions:*

In order to start operating the following steps should be implemented:

1. Turn on the computer.

2. Place the components on the Mounting Frame with the following order:




3- After completing the appropriate wiring, please switch the power cable of the *Power Supply Module Type 5* to the power socket and switch the key of the *Power Supply Module Type 5* to turn in ON. Make sure the built-in circuit-breakers in the components are ON.

## Questions:

1. Which type of the wind turbine provide almost the greatest power and is used in powerful wind power plants?
   a. Horizontal axis propeller type wind turbine with swivel blades
   b. Horizontal axis propeller type wind turbine with non-swivel blades
   c. multi-bladed vertical axis wind turbines with a guiding device

2. The voltage and frequency of the on-grid operation is stabilized by:
   a. regulation of the turbine and excitation current of the generator
   b. usage of the battery, inverter and regulation of the inverter
   c. the voltage and frequency of the grid; the voltage and the frequency are not regulated in wind power plants

3. Which types of wind turbines allow you to adjust the power of the wind power plant with a change in air speed (downward regulation)?
   a. multi-bladed vertical axis wind turbines with a guiding device
   b. Horizontal axis propeller type turbines with rotary blades
   c. Orthogonal Savonius vertical-axial turbines

4. Which type of wind turbine is installed on the Wind Power Generation Trainer?
   a. Horizontal axis propeller type turbines with rotary blades
   b. Horizontal axis propeller type turbines with non-rotary blades
   c. vertical-axial turbine

6. With an increase in the number of poles, the nominal rotational speed of the generator is:
a. Increasing
b. Decreasing
c. Remains stable

7. The maximum rotational speed of the synchronous generator is:
a. 3600 rpm
b. 1800 rpm
c. 1200 rpm

8. In case the rotational speed of an autonomous synchronous generator increases, the frequency is:
a. Increasing
b. Decreasing
c. Remains stable

9. In case of on-grid operation mode, the voltage of the synchronous generator is:

a. higher than the mains voltage
b. lower than the mains voltage
c. equal to the mains voltage

10. How does the voltage and frequency (off-grid operation) of a wind power plant being stabilized without being connected to an electrical grid and supplying a stand-alone load?

11. Describe an asynchronized synchronous generator and its excitation system ?

**Instructions for Preparation of Lab Report**

Before preparing your report, complete the tasks and answer questions throughout the lab sheet.

YOUR Report must include:

- Introduction: A brief about the experiment
- Material and Methods/ Procedure
- Analysis
- Results and Discussion
- Conclusion

The End

Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

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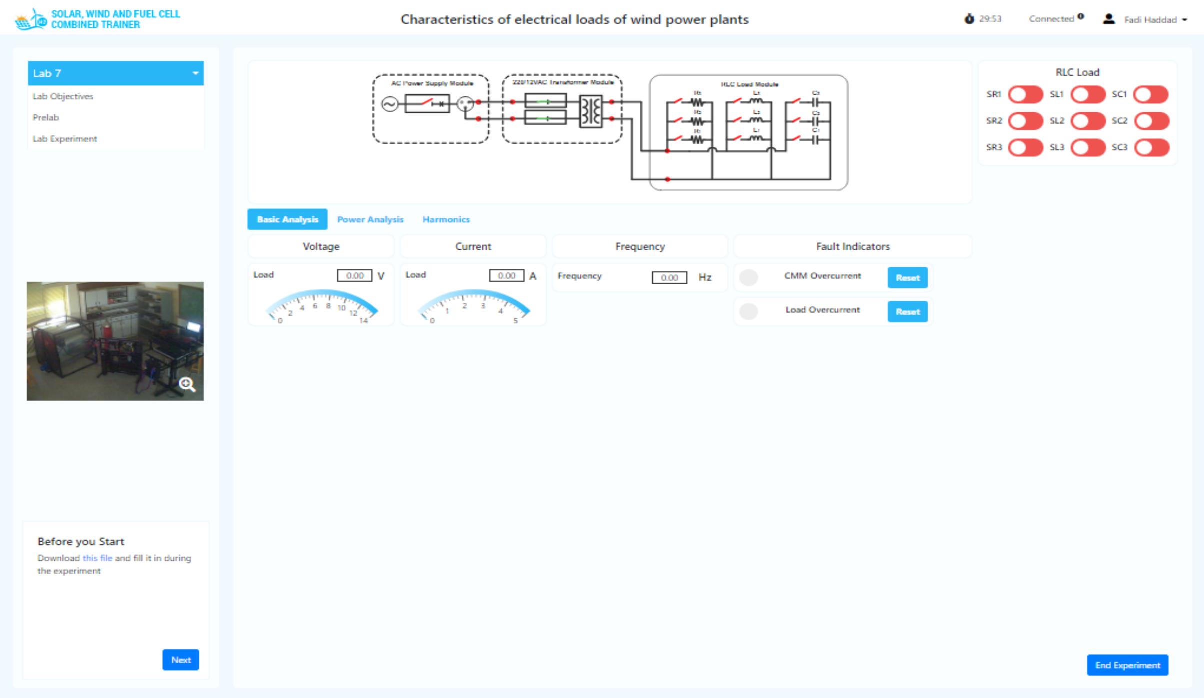
# ***Power Generation Trainer Lab Sheets***

## *Exp No. 7 Wind Power Trainer : Characteristics of electrical loads of wind power plants*

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*Khaled Alawasa*

*Saud Althunibat*

## 2.7 Experiment No. 7 CHARACTERISTICS OF ELECTRICAL LOADS OF WIND POWER PLANTS

### *Introduction*

The electric generators of power plants are considered to be the Industrial electric power sources of AC, which are driven by hydraulic, thermal or wind motors. Generally, the synchronous generators are used in powerful power plants.

The power plants are integrated into power systems, where the generators operate in parallel with each other and provide the specified electric power, voltage and frequency. The groups of consumers of electric current (so-called loads) are connected to various points of the power system. The generators of the power system provide power supply loads in terms of the amount of consumed power and the power quality.
In power systems, the stable voltage and frequency (within acceptable limits) are provided by automatically regulating the excitation current of the generators and the rotational speed of the drive motors.

The wind power generators and wind power plants are considered to be irregular power sources, because the amount of power they produce depends on the air flow and air speed.
Wind power plants operate either with on-grid mode or in battery charging mode supplying a separate load connected to the wind power plant. In the case of on-grid operation of wind power plants, the frequency and the voltage are provided by the power system, and the wind power plant produces power in accordance with the power of the air flow and transfers it to the grid.
In case of off-grid mode, the wind power plant operates with a battery, which (with sufficient power of the air flow) is charged from the generator, and the generator can also supply a separate load. In case the airflow is insufficient or there is no airflow, the AC load is powered by the battery through the inverter. The voltage frequency on the load in this case is provided by the inverter, and the load voltage is determined by the battery voltage. The indicated operation modes and their characteristics are studied in the Labs 8 and 9.

**The Load parameters are as follows:**

- the amount of consumed current and power.
- the power factor of the consumed current cos $\varphi$, where $\varphi$ is the angle between the voltage and the consumed current; the power factor depends on the nature of the resistances and their relationships in the load circuit - active, inductive and capacitive.
- The load parameters are considered to be a commercial indicator for mutual settlements between the energy system and the consumer.

**The basic quality parameters of the generated power are:**

- the magnitude of voltage and its deviation from the nominal value.
- the frequency value and its deviation from the nominal value.

- the distortion coefficient of the sinusoidal shape of the electric voltage curve.
- -The deviation of power quality parameters from standardized values leads to increased energy losses and economic damage.

**In the specified conditions, it is necessary:**

- to get acquainted with various types of electrical loads - active, inductive, capacitive and their combinations,
- to study the methods for measuring current, voltage, power, frequency, power factor, sinusoidal distortion of the shape of the electric voltage curve,
- practical calculations and measurements of these load parameters to ensure the operation of power supply systems and commercial calculations.
- Characteristics of electrical loads

Electric loads are divided into the following types: active, inductive, capacitive and their combinations.

Active loads are considered to be active resistors and consumers, in which an active power is allocated: mechanical, thermal, radiation power, and power losses. Purely active loads are considered to be the lighting and electric heaters, DC consumers, feeding through rectifiers: DC motors, consumers of chemical industries.

Inductive loads are the ones that are representing an inductance in which a current flows lagging behind the phase voltage by 90º. Inductive loads are magnetizing currents of transformers and asynchronous motors.

Active-inductive loads are considered to be combinations of active and inductive loads. The most common active-inductive loads are asynchronous electric motors.
Capacitive loads are considered to be the loads that represent a capacitance in which a current flows, leading phase voltage by 90º. Practically capacitive loads, with negligibly small active component, are considered to be compensating capacitors in power supply systems, as well as the leakage circuits in power supply lines.

Active-capacitive loads are considered to be combinations of active and capacitive loads. In case of active capacitive load, the current is ahead of the phase voltage

Vector diagrams of various types of loads are shown in Figure 2.30 - Figure 2.36

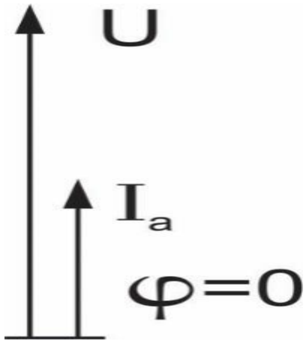



Figure 2-30 Active Load

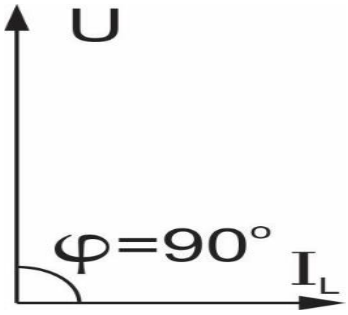



Figure 2-31 Inductive Load

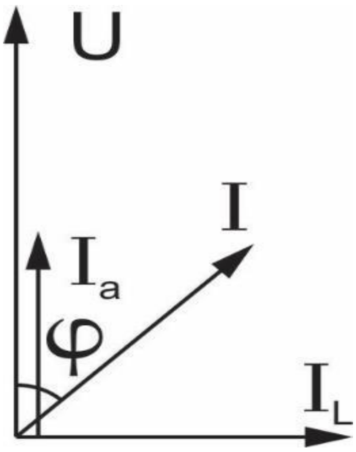



Figure 2-32 Active-Inductive Load

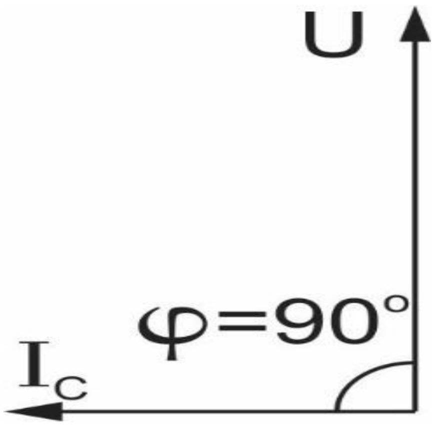



Figure 2-33 Capacitive Load

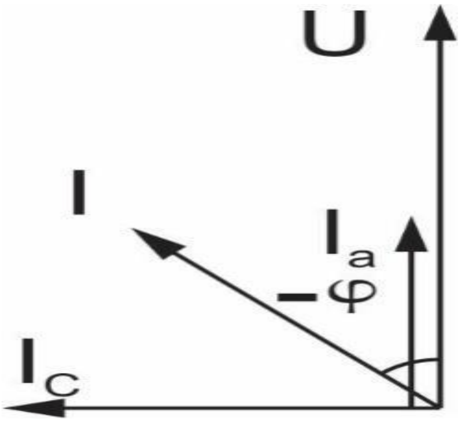



Figure 2-34 Active-Capacitive Load

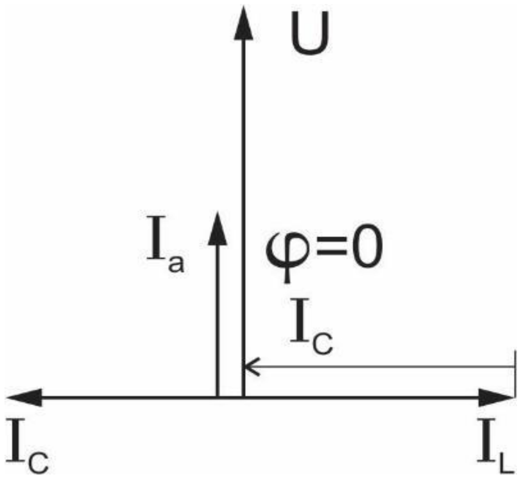



Figure 2-35 Active-inductive-capacitive load with full compensation

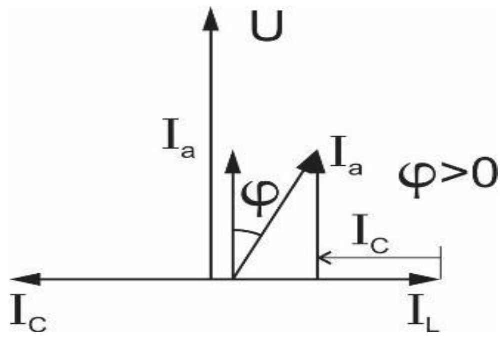


*Figure 2-36 Active-inductive-capacitive load with incomplete compensation of reactive currents, where the inductive component predominates*

The components of the load currents when connected in parallel can be expressed through the applied voltage and the load resistance.
Active current:

$$Ia=U/R \qquad (1)$$

where *U* – voltage, *R* – active load resistance.

Reactive current:
In case of inductive load:

$$Ir=IL=U/XL=U/\omega L \qquad (2)$$

where *U* – voltage, *XL* – inductive load resistance, *L* – load inductance, *ω = 2 π f* – angular frequency, *f* – frequency AC voltage,
In case of capacitive load:

$$Ir=Ic=U/Xc=U/(1/\omega C)=U\omega C \qquad (3)$$

where U – voltage, X*c* – load capacitance, *C* – load capacity.
Total load current

$$I=\sqrt{Ia^2+Ir^2} \qquad (4)$$

The components of the load currents, based on the vector diagrams in Figure 6-3 and Figure 6-5 can be expressed in terms of the total current *I* and the phase angle *φ* between the voltage and current vectors:

$$Ia=I\cos\varphi \qquad (5)$$

$$Ir=I\sin\varphi \qquad (6)$$

The Inductive and capacitive currents, accordingly, the reactive inductive and capacitive power can compensate each other.

The complete compensation is shown on the Figure 6-6, the incomplete compensation is shown on the Figure 6-7 where the inductive component predominates. In these cases, with active-inductive-capacitive load, the total load current will be:

$$I=\sqrt{Ia^2+(IL-Ic)^2} \qquad (7)$$

The total load power in a single-phase system is generally equal to:

$$S=U\,I \qquad (8)$$

where *U* – voltage, *I* – total load current.

The total power has the components of active and reactive power.
Active power:

$$P = U\,I\cos\varphi = U\,I_a \qquad (9)$$

where *U* – voltage, *I* – total load current, *φ* – phase angle between voltage and current vectors, $I_a$ – active current component.

Reactive power:

$$S_r = U\,I\cos\varphi = U\,I_r \qquad (10)$$

Total load power

$$S = \sqrt{P^2 + S_r^2} \qquad (11)$$

The power factor cos *φ* can be expressed in terms of load impedance components as follows.
In case of active-inductive voltage:

$$\cos\varphi = I_a/I = 1/1 + (R/\omega L)^2 \qquad (12)$$

In case of active-capacitive voltage:

$$\cos\varphi == 1/1 + (\omega RC)^2 \qquad (13)$$

The power factor can be expressed with outside parameters – voltage *U,* total current *I* and active power *P* in the following way:

$$\cos\varphi = P/U\,I \qquad (14)$$

The total load power in a 3-phase system is generally equal to:

$$S = \sqrt{3}\,U_l I \qquad (15)$$

where $U_l$ is the linear voltage, (I*)* is the total load current. Similarly, the components of power are expressed.

### *Objectives*

- To get acquainted with various types of electrical loads: active, inductive, capacitive and their combinations
- To study the methods for calculating and measuring current, voltage, power, frequency, power factor.

### *Experiment Components:*

1. **Application Software Description**
2. **AC/DC Transformer Module**
3. **RLC Load Module includes:**
    - SR1, SR2, SR3 switches – switches ON and OFF each stage of the Resistive load
    - SL1, SL2, SL3 switches – switches ON and OFF each stage of the Inductive load

- SC1, SC2, SC3 switches - switches ON and OFF each stage of the Capacitive load

**4- Control and Measurement Module block includes:**

- Voltage RMS (L1) – shows the RMS values of the phase voltages
- Current RMS (L1) – shows the RMS values of the phase currents
- Frequency (Hz) – shows the voltage frequency
- Active Power (W) – shows the active power per phase
- Reactive Power (VAR) - shows the reactive power per phase
- Apparent Power (VA) - shows the apparent power per phase
- Vector Diagram
- Voltage THD, Current THD (%)

### *Step by Step Instructions*

To investigate the measurement of the generated current voltage and power, the following steps should be implemented:

1. Open Lab7 in the software
2. Below please find the screenshot of Lab 7>>System Layout tab

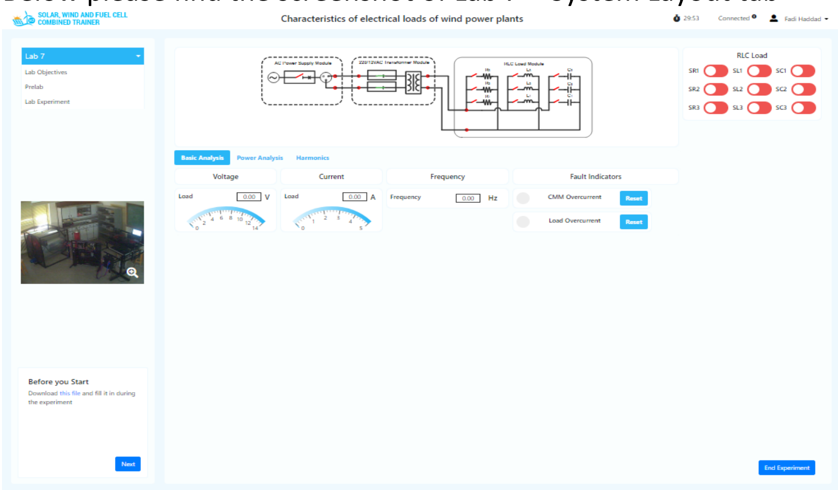



*Figure 2-37 Lab screenshot*

3. Carry out calculation for each type of the load by determining the following load parameters according to Equations 1-14 given in Prelab

   a. Current: active, reactive component and total current

   b. Power: active, reactive components and total power

   c. Power factor

**Initial calculation data:**

- The phase voltage – 12V
- The active resistances of each resistive load sections – *50 Ohm, 20 Ohm and 10 Ohm (SR1, SR2 and SR 3 respectively)*

- The active power of each section in the resistive load at a nominal phase voltage of 12 V should be up to – *14 W*
- The total active load power should be approximately *24.5 W*, in case all three load switches are on.

. Inductance of each inductive section – 28 mH

. Capacity of each capacitor section - *250 µF*

. Reactive power of each section of the reactive load should be approximately *12 VA* in case of nominal phase voltage of 12 V

- The total reactive load power should be approximately *36 VA* in case all three load switches are on.

The load power is achieved from the grid via AC/DC *Transformer Module*. In this case, a single-phase supply voltage can be arbitrarily connected to any phase of the load: Capacitive, Inductive or Resistive. **Table 2.10** shows the connections to phase 1.

4. From the software switch the switches of *RLC Load Module* according to **Table 2.10**. In the experiments N1-6, the maximum load is obtained, i.e. all three load switches in each component are switched on. In the experiment N7, two SC switches are switched on in order to have incomplete compensation.

5. Implement the measurements in the software for the following real load parameters:

d. Basic Analysis tab>>Voltage RMS L1, Current RMS L1, Frequency L1

e. Power Analysis tab>>Active Power L1, Reactive Power L1, Apparent Power L1

f. Power Factor tab>>Power Factor L1

g. Harmonic Analysis tab>> Voltage THD L1, Current THD L1

*Table 2-10 Load resistance switching diagram*

| **Active Resistance** | | | **Inductance** | | | **Capacity** | | |
|---|---|---|---|---|---|---|---|---|
| Min | Mid | Max | Min | Mid | Max | Min | Mid | Max |
| R1 | R2 | R3 | R1 | R2 | R3 | R1 | R2 | R3 |
| *R = 50 / 3 = 16,6 Ohm* | | | *L = 28 / 3 = 9,33mH* | | | *C = 250 X 3 = 750 µF* | | |

The table illustrates the mode of the circuit breakers for each of the experiment. The darkened cells show the ON mode of the circuit breaker, the undarkened cells show the Off mode of the circuit breaker.

*Table 2-11 Comparative results of calculated and measured values*

| *Load characteristics* | *Parameter* | *Calculation equations* | *Calculated value* | *Measured value* | *Deviation* |
|---|---|---|---|---|---|
| *Active*<br>*Inductive*<br><br>*Capacitive*<br>*Active-inductive*<br>Active-capacitive | *Load, V* | | *12* | | |
| | *Total current, A* | *I=√(Ia^2+Ir^2 ) …………….(4)* | | | |
| | *Active power, kW* | *P=U I cos φ=U Ia …………(9)* | | | |

| | | | | | |
|---|---|---|---|---|---|
| *when U=12V* And *U=15V* | *Power factor, cos φ* | $1/1+(R\omega L)^2$ *.....(12),* $1/1+(\omega RC)^2$, *.......(13),* $\cos\varphi = P/UI$ *..........(14)* | | | |
| | *Distortion factor, Df* | | | | |

**Experiments:**

• Insert the calculated and the measured load parameters in the Table 2.1-2. For each of the parameter, the deviation of the measured value from the calculated value is calculated (expressed in %)

Deviations of the measured parameters from the calculated ones will inevitably occur due to the presence of internal active resistances in the coils of inductances and in the capacitors, as well as in the connecting wires and contacts, which are not included in the calculated equations.

• Draw the vector diagrams similar to those shown in Figure 2.1-1 - Figure 2.1-7, according to the measured values of voltage, current, power factor, performed in accordance with point 5 (Step by step instructions), as well as the calculated values of active and reactive components performed in accordance with the point 3 (Step by step instructions), in the selected scale.

## Questions

1. How does the active power change when the active load resistance increases?

a. Increases

b. Decreases

c. Remains stable

2. To compensate the inductive reactive current, the capacitor must be:

a. More than the inductive one

b. Less than the inductive one

c. Equal to the inductive one

3. The value of the active power is affected by the value:

a. Active current

b. Inductive current

c. Capacitive current

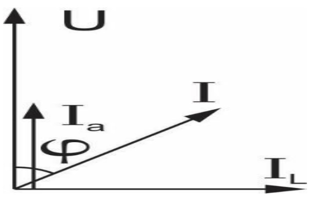
4. With active-inductive load, the load current:

a. Leads the voltage

b. Lags the voltage

c. Coincides in phase with the voltage

5. Display a vector diagram with an active-inductive load ?




**<u>Instructions for Preparation of Lab Report</u>**

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- YOUR Report <u>must</u> include:
    - Introduction: A brief about the experiment
    - Material and Methods/ Procedure
    - Analysis
    - Results and Discussion
    - Conclusion

The End

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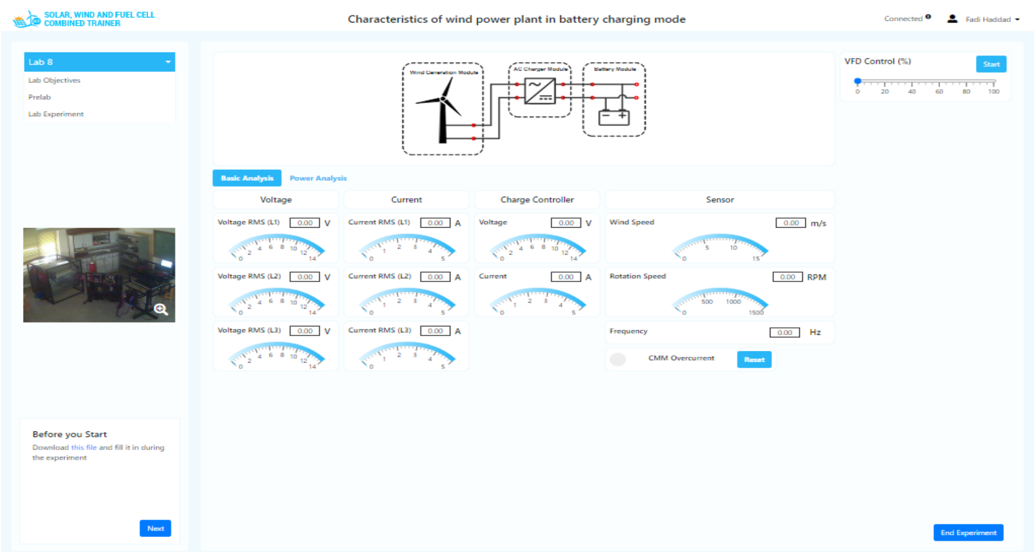
# *Power Generation Trainer Lab Sheets*

## *Exp No.8 Wind Power Trainer: Characteristics of wind power plants in battery charging mode*

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*Reviewed by: Ziyad Altarawneh*
*Khaled Alawasa*
*Saud Althunibat*

## 2.8 Experiment No. 8 Characteristics of wind power plants in battery charging mode

### Introduction

The wind power plant can operate off-grid (autonomously without being connected to the power grid). In this case, the power generated by the generator can be used to power the autonomous load and to charge the battery. In this case, of course, the amount of power consumed by the stand-alone load and the battery is equal to the power that the generator generates.

The active power that a generator can generate is determined by the power of the air flow that drives the wind power generator. The power of the air flow, in its turn, is determined by the air flow speed. The active power generated by the generator is equal to the active power that the load connected to the generator consumes. Thus, the active power generated by the generator and the active power consumed by the load are always equal to each other at a certain frequency and voltage of the generator.

If, for example, at a constant speed and power of the air flow, the active load resistance increases, i.e. the active load power will decrease, this will lead to an increase in the speed, frequency and voltage of the generator to such an extent that the power balance of the generator and the load will be restored at the new higher values of speed, frequency and voltage of the generator. The frequency and voltage of the generator, according to the standards, should be unchanged, equal to the nominal, regardless of the operating conditions of the wind power plant. This requirement is provided by means of an automatically adjustable ballast active load, also connected to the generator, as follows.

In case when the airflow rate, the battery charge power or the autonomous external load changes, the active power of the ballast load is automatically changed to the point that the speed, frequency and voltage of the generator are set at nominal speed: *360 rpm, 60 Hz, 12 V* - with permissible deviations.

The active load of the generator is the total value of the battery charge active power, the active power of the external autonomous load and the active power of the adjustable ballast load. The active power balance of the wind power generator is expressed as follows.

$$Pa = Pg,$$

$$kV^3 = U^2/Rb + U^2/Pl + U^2/Rc = U^2(1/Rb + 1/Pl + 1/Rc) = U^2 G_б, \quad (1)$$

where $Pa = kV^3$ is the power of the air flow, $V$ - the air flow speed, $k$ - the coefficient of proportionality, including the efficiency of the wind power generator and power conversion, $Pg$ - the generator's active power, $U$ - the generator voltage, $Rb$, $Pl$, $Rc$ - respectively active resistors of battery, autonomous external load and adjustable ballast load, $G_б$ - the total active conductivity of the load connected to the generator. Thus, each air flow speed must correspond to a certain value of the active conductance of the total load, at which the rotational speed, frequency and voltage of the generator are equal to the nominal values within the permissible deviations.

The generation of the electric power by the wind power generator and the necessary consumption of electric power by the consumer do not coincide both in magnitude and in time: the power generation is determined by the wind flow, which varies arbitrarily, and the power consumption is determined by the load curve of the consumer also arbitrarily, and they, of course, do not coincide. The surplus of the generated power supplies the ballast load.

To reconcile the generated and consumed energy on the wind power plant, a Battery Module is installed.

The Battery Module is aimed to store the power (when the wind generator generates power) and to use it for powering a stand-alone load when the magnitude of the generated power is insufficient due to insufficient power of the air flow or its absence. The battery accumulates electric power in the form of a direct current with a voltage of *12 V*.

The battery is charged by the Charge Controller Module which includes a rectifier and an automatically adjustable ballast load. The battery is charged with DC. The magnitude of the charging current is regulated automatically depending on the charging degree of the battery.
The charging current is automatically maintained at approximately 10% of the battery rated current of the battery in order to ensure its reliability and durability.

The capacity of the Battery Module that is installed on the Wind Power Generation Trainer is of 5Ah. The nominal current of the Battery Module in the mode of a one-hour discharge is 5A, therefore, the battery charge should be performed with a current of 0.5 A.
The battery charging mode and supplying the autonomous load mode are functionally separated.

### Objectives*:*

To study the operation and characteristics of wind power plant in battery charging mode

### Experiment Components:

- **VFD Start (VFD Block)** – starts the VFD Block
- **VFD Frequency (VFD Block)** – the user can adjust the VFD Frequency which is measured in %.
- **Control and Measurement Module block includes**:
- **Voltage RMS (L1, L2, L3)** – shows the RMS values of the phase voltages
- **Current RMS (L1, L2, L3,)** – shows the RMS values of the phase currents
- **Charge Controller (Voltage)** – shows the output voltage of the Charge Controller
- **Charge Controller (Current)** – shows the output current of the Charge Controller
- **Wind Generator** – shows the total active power of the Wind Generator
- **Charge Controller** – shows the active power of the Charge Controller
- **Power Factor** – shows the total power factor of the Wind Generator
- **Frequency (Hz)** – shows the voltage frequency
- **Wind Speed** – shows the wind speed

## Application Software Description:

Below is the screenshot of Lab 8

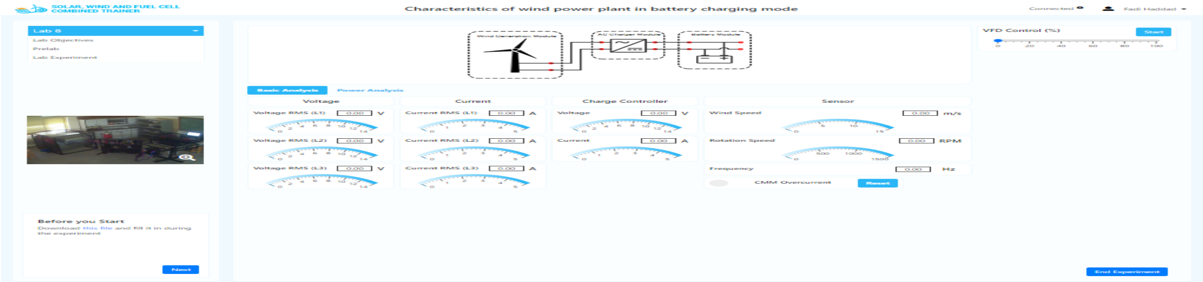


*Figure 2-38 Lab Screenshot*

## Step-by-step instructions:

To investigate the characteristics of wind power plant in battery charging mode, the following steps should be implemented:

1. Open Lab 8 in the software

In this lab, the battery charge from the generator must be investigated at air flow in the range of 8 m/s up to a 10 m/s. The value of the ballast current is automatically regulated from the condition of providing the generator's nominal parameters: generator speed-3600 rpm, frequency-50 Hz, voltage-12 V and - with allowable deviations. (The deviations within ± 10% of the nominal values are acceptable).

To build the characteristics, the electrical parameters of the generator should be carried out at a given airflow rate in the range from 8m/s up to 10 m/s.

**The experiment is carried out in the following sequence of actions:**

1. Start the VFD from the software. By adjusting the VFD Frequency on the software, obtain the following airflow speed: 6 m/sec, 8 m/s, and 10 m/s.
2. At each point of the wind flow speed, fix the values of Generator Frequency, Generator Voltage, Generator Current, Generator Active Power, Generator Power Factor, Charge Controller Current, Charge Controller Voltage, Charge Controller Power.

***Please note**: When the Battery Module is fully charged, the Charge Controller Module Type 1 will automatically brake the Wind Generator.*

## Experiments:

1.Insert the measured values in the Table 2.12

The power factor is determined based on the measured values as follows:

$$\cos \varphi = P / S = P / U I. \quad (2)$$

2. Draw a graphical dependence of the generator active power on the air flow speed:

$$P = F(V).$$

$U(B) = F_1 I(A)$, $U_a(B) = F_2 I(A)$ where $\cos \varphi = 1$, $\cos \varphi = 0{,}8$, $\cos \varphi = -0{,}8$,

3. Determine the accuracy of maintaining the voltage on the load and on the battery:

$$\Delta Ub = \pm [(Ub\ max - Ub\ min) / 2].$$

*Table 2-12*

| Air flow rate *V, m/sec* | 6 | 8 | 10 |
|---|---|---|---|
| ***Generator*** | | | |
| **Generator Frequency, *f, Hz*** | | | |
| **Generator Voltage, *U, V*** | | | |
| **Active power of the generator, *P, W*** | | | |
| **Generator Current, *I, A*** | | | |
| **Generator power factor, *cos φ*** | | | |
| ***Battery*** | | | |
| **Charge controller current, *Ia, A*** | | | |
| **Charge controller voltage, *Ua, V*** | | | |
| **Charge controller power, *Pa, W*** | | | |

**Questions:**

1. In case of an increase in the rotational speed of a synchronous generator with permanent excitation magnets operating without connecting to the grid, its voltage:
   a) increases
   b) decreases
   c) remains stable

2. How is the battery module charged?
   a) AC
   b) DC (coinciding polarity) (+source c+ battery, -c-)
   c) DC (opposite polarity) (+source - battery, -c+)

3. The most appropriate value of the Charge Controller (in % from nominal values)
   a) 10%
   b) 20%
   c) 50%

4. As the reactive current of the generator increases, its active power:
   a) increases
   b) decreases
   c) remains stable

5. What is the aim to connect Battery module between the generator and the load?

## Instructions for Preparation of Lab Report

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- YOUR Report must include:
  - Introduction: A brief about the experiment
  - Material and Methods/ Procedure
  - Analysis
  - Results and Discussion
  - Conclusion

The End

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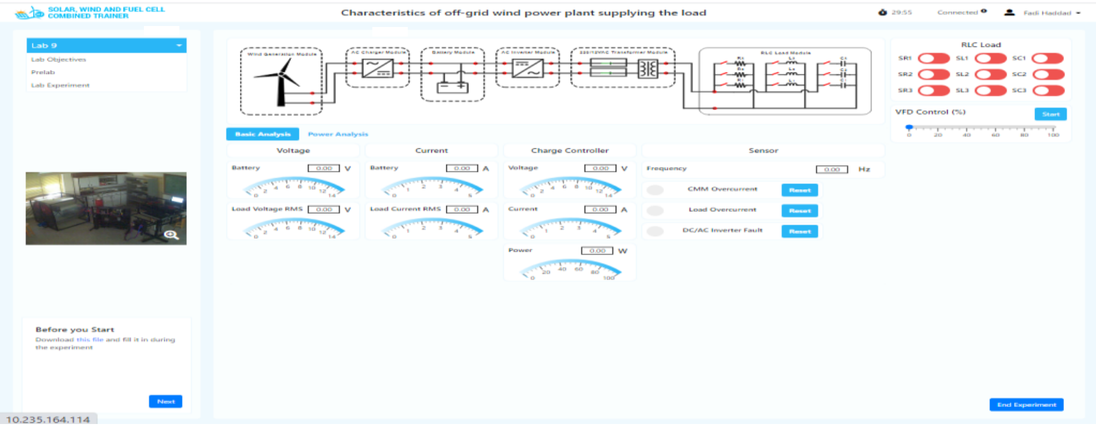
# *Power Generation Trainer Lab Sheets*

## *Exp No.8 Wind Power Trainer: Characteristics of off-grid wind power plant supplying the load*




*Prepared by: Walaa Al Saraireh*
*Firas Al-Adayleh*
*Reviewed by: Ziyad Altarawneh*
*Khaled Alawasa*

## 2.9 Experiment No. 9 Characteristics of off-grid wind power plant supplying the load

**Introduction:**

In the wind power plant, the charge and discharge of the battery are functionally divided as follows:

**1. Battery charge**: The battery is charged from the generator in cases where the generator's power is sufficient to provide the power of the battery charge. The active power that a generator can generate is determined by the magnitude of the air flow that drives the wind power generator. The magnitude of the air flow, in its turn, is determined by the air flow speed, which is irregular, because depends on natural conditions. The power of the battery charge depends on the degree of charge of the battery (it is expressed by the voltage at the battery terminals), which is also irregular, because depends on the arbitrary consumption of current from the battery. Therefore, the battery can be charged only at certain irregular intervals when the power generated by the generator is sufficient to charge the battery.

2. **Battery discharge:**The battery is discharged in cases where the battery supplies the load connected to the battery. The external load of the wind power plant is also irregular - it must be supplied irrespective of the magnitude of the air flow, accordingly, of the power generated by the generator. It is possible to provide a separate supply of an external load under the specified conditions if the power supply of the load is performed from the battery through the frequency converter of the inverter. The frequency converter converts the DC voltage of the battery into AC voltage of the load supply with a constant frequency of *60 Hz.* The voltage of the load is determined by the voltage of the battery - this voltage is not regulated.

The specified operating mode is implemented on the wind power generation trainer. In this case, the so-called buffer operation mode of the battery is being operated, when the battery is charged irrespective of the load, and the load is supplied separately from the power generated by the generator, up to the stopped and idle generator.

***Objectives***

To study the operation and characteristics of wind power plant supplying the load.

***Experiment Components:***

- RLC Load Module
- AC/DC Transformer Module
- DC to AC Inverter Fault
- VFD Start (VFD Block) – starts the VFD Block
- VFD Frequency (VFD Block) – the user can adjust the VFD Frequency which is measured in %.
- Control and Measurement Module block includes:
- Voltage (Battery, Load Current RMS) – shows the voltage value of the Battery and the Load
- Current (Battery, Load Current RMS) – shows the current value of the Battery and the Load
- Frequency (Hz) – shows the voltage frequency

### *Application Software Description:*

Below is the screenshot of Lab 9>>System Layout tab

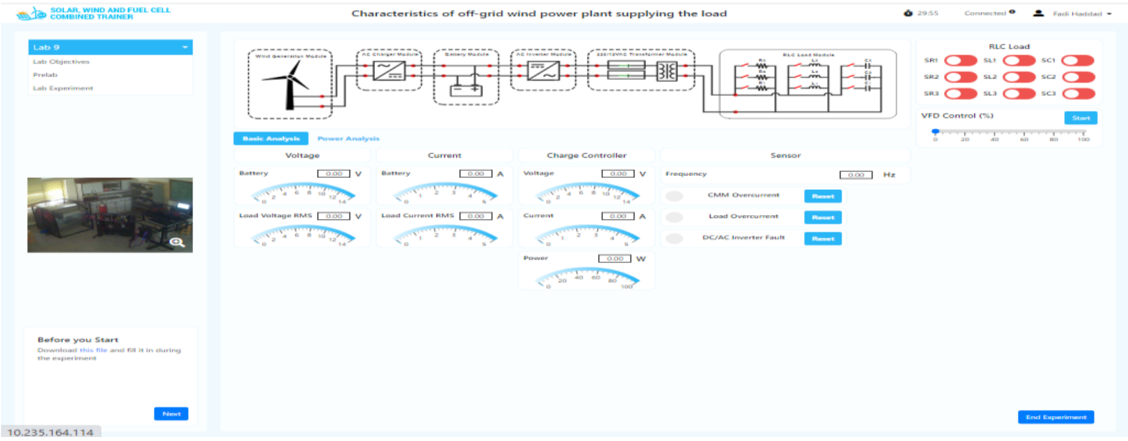



*Figure 2-39 Lab Screenshot*

### *Step-by-step instructions*

To investigate the characteristics of wind power plant supplying the load, the following steps should be implemented:

1. Open Lab 9 in the software

• In this lab, the stand-alone load will be supplied from the battery through the Load voltage RMS without air flow and the external characteristics will be defined.

***Please note****: that in this lab the Battery module is used as a power source. In case the battery voltage is below the minimum limit, a pop up will appear in the software to prompt you to charge the battery.*

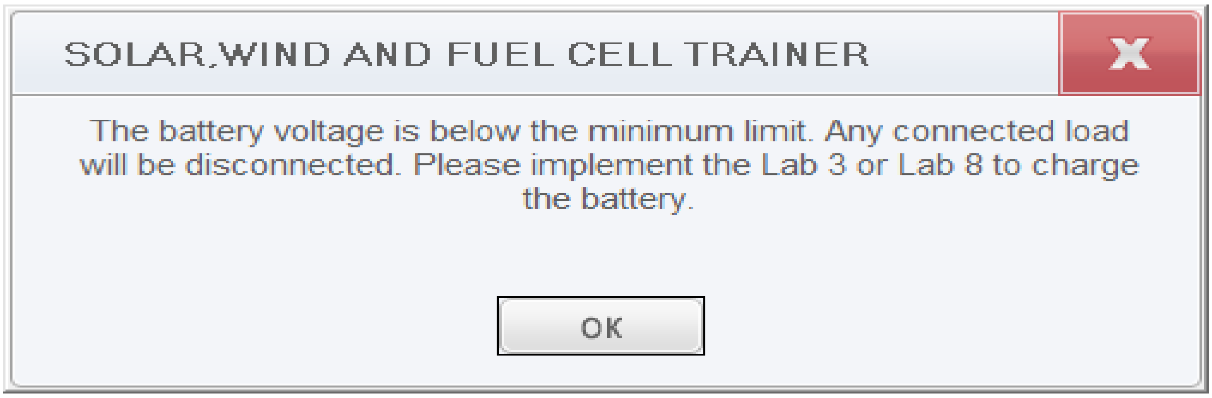



*Figure 2-40 Low Battery Warrning message*

**The experiment is carried out in the following sequence of actions**:
1. Turn on the AC/DC *Transformer Module* by first checking the Enable Module checkbox and then pressing the Remote Start button.

2. From the software switch the SR switches of *RLC Module* in order. At each position determine the following load parameters:

• Battery voltage

• Load voltage RMS

• Load active power

• Load current RMS

• Load power factor

## *Experiments:*

1. Insert the measured values in the Table 2.13

*Table 2-13*

| Load stages | 1 | 2 | 3 |
|---|---|---|---|
| Battery voltage, U*a, V* | | | |
| Load voltage RMS, *U, V* | | | |
| Load active power, *P, W* | | | |
| Load current RMS, *I, A* | | | |
| Load power factor, *cos φ* | | | |

The power factor is determined based on the measured values as follows:

$$\cos \varphi = P / S = P / U I \qquad (1)$$

2. Draw an external characteristic: the graphical dependence of the voltage on the load (at the output of the DC to AC Inverter Module) from the load current for a given power factor:

$$U = F(I) \qquad (2)$$

Determine the accuracy of maintaining the voltage on the load and on the battery:

$$\Delta U = \pm [(U_{max} - U_{min}) / 2] \qquad (3)$$

$$\Delta U_b = \pm [(U_{b\,max} - U_{b\,min}) / 2] \qquad (4)$$

***Questions:***

1. In case of battery discharge, the voltage at its terminals
   a. increases
   b. decreases
   c. remains stable

2. When the inverter is loaded, the frequency of the output voltage of the inverter
   a. increases
   b. decreases
   c. Remains stable

3. When the battery is loaded, the voltage at its terminals
   a. Increases
   b. Decreases
   c. Remains stable

4. When the battery is loaded through the inverter by an active-reactive load, the voltage at its terminals in comparison with the loading by the active load
   a. Increases
   b. Decreases
   c. Remains stable

5. Why does the active-reactive load reduce the battery voltage more than the purely active load at the same active power?

**Instructions for Preparation of Lab Report**

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- YOUR Report must include:
    - Introduction: A brief about the experiment
    - Material and Methods/ Procedure
    - Analysis
    - Results and Discussion
    - Conclusion

The End

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# *Power Generation Trainer Lab Sheets*

## *Exp No.10 Hydrogen Fuel Cell Trainer: the load structure and design of hydrogen fuel cell*

*Prepared by: Walaa Al Saraireh*
*Firas Al-Adayleh*
*Reviewed by: Ziyad Altarwneh*

## 2.10 Experiment No. 10 Hydrogen fuel cell: the load structure and design of hydrogen fuel cell

### Introduction

The first fuel cell was demonstrated in the middle of the 19th century by a scientist named William Grove. In a fuel cell a reaction takes place where hydrogen and oxygen recombine into water and thereby releasing electrical energy. The chemical formula of the reaction is seen in *equation 1*

$$2H_2o + O_2 \rightarrow 2H_2O + Energy \qquad [1]$$

In the energy field, most hydrogen is used through Fuel Cells (FCs). A fuel cell is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as by-products. In its simplest form, a single fuel cell consists of two electrodes - an anode and a cathode - with an electrolyte between them, see **Figure 2.41**. At the anode, hydrogen reacts with a catalyst, creating a positively charged ion and a negatively charged electron. The proton then passes through the electrolyte, while the electron travels through a circuit, creating a current. At the cathode, oxygen reacts with the ion and electron, forming water and useful heat.

A typical fuel cell works by passing hydrogen through the anode of a fuel cell and oxygen through the cathode. At the anode site, a catalyst splits the hydrogen molecules into electrons and protons. The protons pass through the porous electrolyte membrane, while the electrons are forced through a circuit, generating an electric current and excess heat. At the cathode, the protons, electrons, and oxygen combine to produce water molecules. As there are no moving parts, fuel cells operate silently and with extremely high reliability.

The electrodes are normally made flat and porous to achieve good contact between the electrolyte and the gases. The layer of electrolyte is made thin for the purpose to allow ions to pass through it without too much ohmic losses.

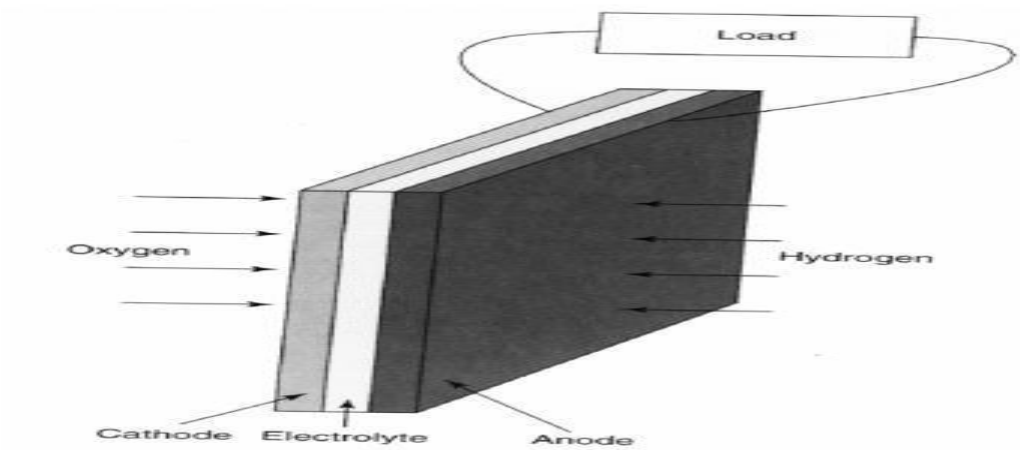



*Figure 2-41 Basic structure of a fuel cell*

It generates electricity through an electrochemical reaction, not combustion. In a fuel cell, hydrogen and oxygen are combined to generate electricity, heat, and water. Fuel cells are used today in a range of applications, from providing power to homes and businesses, keeping critical facilities like hospitals, grocery stores, and data centers up and running, and moving a variety of vehicles including cars, buses, trucks, forklifts, trains, and more.

Fuel cell systems are an efficient, reliable, and quiet source of power. Fuel cells do not need to be periodically recharged like batteries, but instead continue to produce electricity as long as a fuel source is provided.

Due to their chemistry, fuel cells are very clean. Fuel cells that use pure hydrogen fuel are completely carbon-free, with their only byproducts being electricity, heat, and water. Some types of fuel cell systems are capable of using hydrocarbon fuels like natural gas, biogas, methanol, and others. Because fuel cells generate electricity through chemistry rather than combustion, they can achieve much higher efficiencies than traditional energy production methods such as steam turbines and internal combustion engines. To push the efficiency even higher, a fuel cell can be coupled with a combined heat and power system that uses the cell's waste heat for heating or cooling applications.

A fuel cell, uses an external supply of chemical energy and can run indefinitely, as long as it is supplied with a source of hydrogen and a source of oxygen (usually air). The source of hydrogen is generally referred to as the fuel and this gives the fuel cell its name, although there is no combustion involved. Oxidation of the hydrogen instead takes place electrochemically in a very efficient way. During oxidation, hydrogen atoms react with oxygen atoms to form water; in the process electrons are released and flow through an external circuit as an electric current.

Fuel cells can vary from tiny devices producing only a few watts of electricity, right up to large power plants producing megawatts. All fuel cells are based around a central design using two electrodes separated by a solid or liquid electrolyte that carries electrically charged particles between them. A catalyst is often used to speed up the reactions at the electrodes. Fuel cell types are generally classified according to the nature of the electrolyte they use. Each type requires particular materials and fuels and is suitable for different applications.

**Technical and physical description of a fuel cell**

Electrical energy is produced when hydrogen reacts at the anode and oxygen at the cathode. To release it, an activation energy must be supplied in order to overcome the energy hill. The reaction has the form shown in Figure 2.42. If the probability of a molecule having enough energy is low a slow reaction takes place. This is not the case for fuel cell reactions at very high temperatures. To speed up the reaction the most common solutions are:

- Increasing the electrode area
- The use of catalysts
- Raising the temperature

The latter two are applicable to any chemical reaction. The first one is the most important when working with fuel cells. The hydrogen fuel and OH - ions comes in contact on the surface of the electrode, and at the same time the produced electrons must be removed. The time that this takes, is reversed proportional to the area of the electrode, i.e. the larger the electrode area is, the less time it takes. The area is such an important issue that the performance of a fuel cell is expressed in ampere/cm^ 2. The area of an electrode is not only length × width. The material used is, as mentioned before, made highly porous which gives the benefit of an increased effective surface area.

The electrodes in modern fuel cells have a microstructure that makes the effective area hundreds or even thousands times larger than the straightforward area. For practical fuel cells the micro structural design and manufacture of the electrode is an important matter. Other considerations in the design are that catalysts may be added to the material and that the electrode has to withstand high temperatures in a corrosive environment. What counts as a high temperature depends on which type of cells that are used. For a low temperature PEM fuel cell a high temperature is around 80°C.

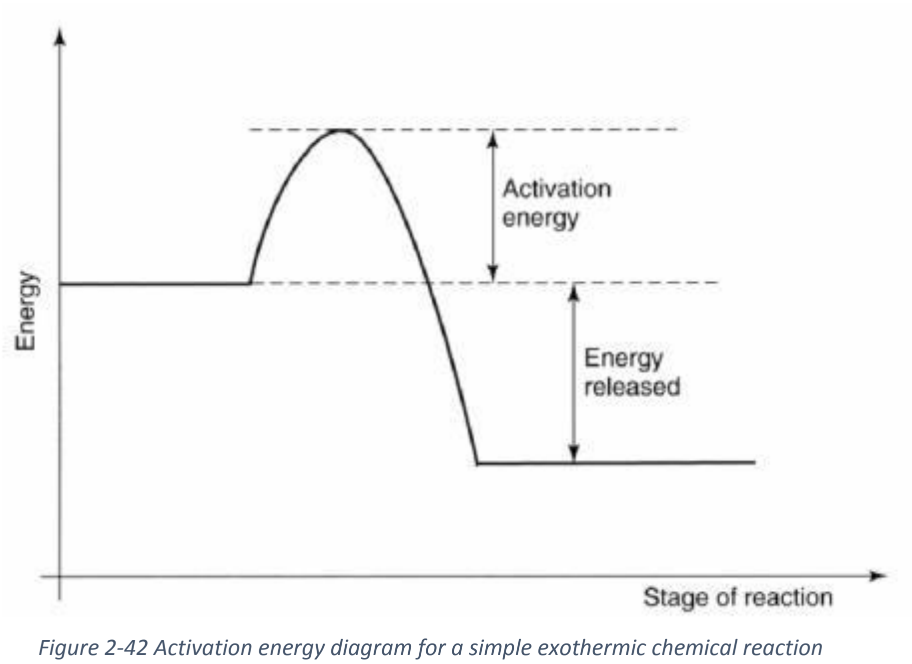
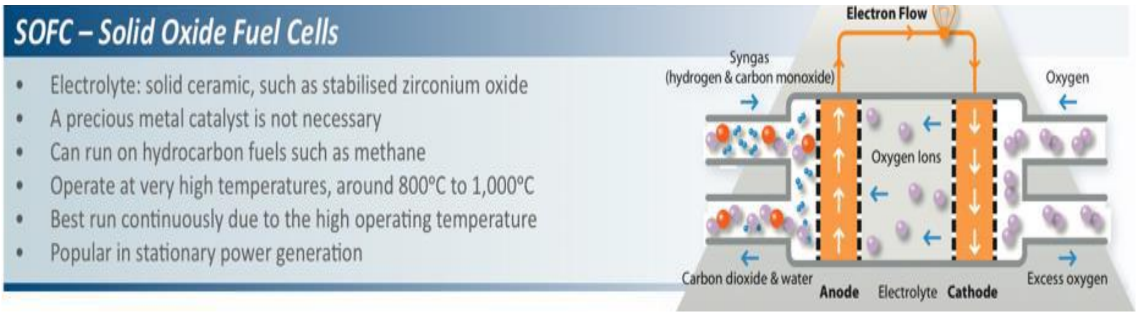


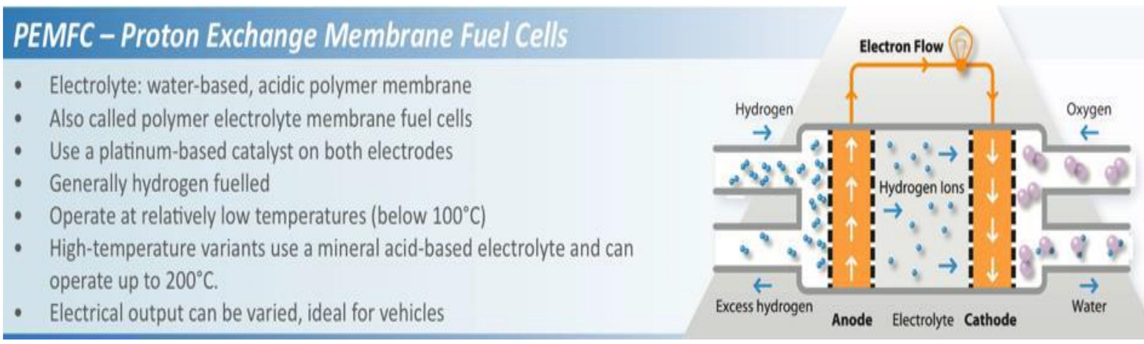

*Figure 2-42 Activation energy diagram for a simple exothermic chemical reaction*

## Fuel Cell Types:

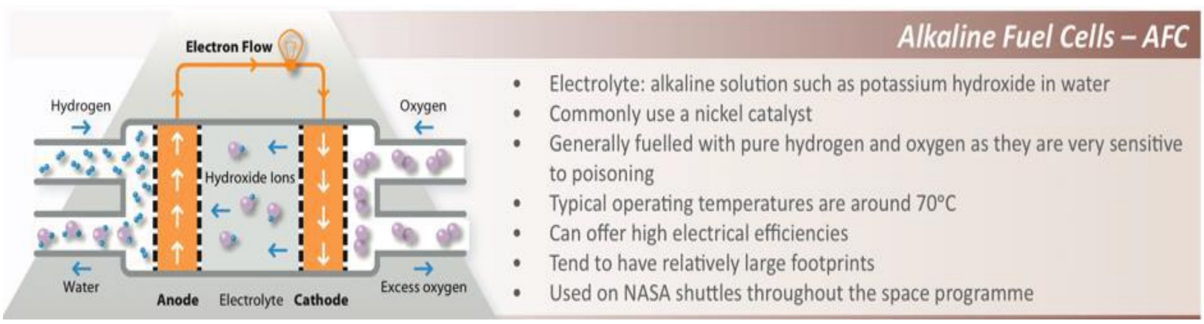
1. **Solid Oxide Fuel Cells (SOFC)**



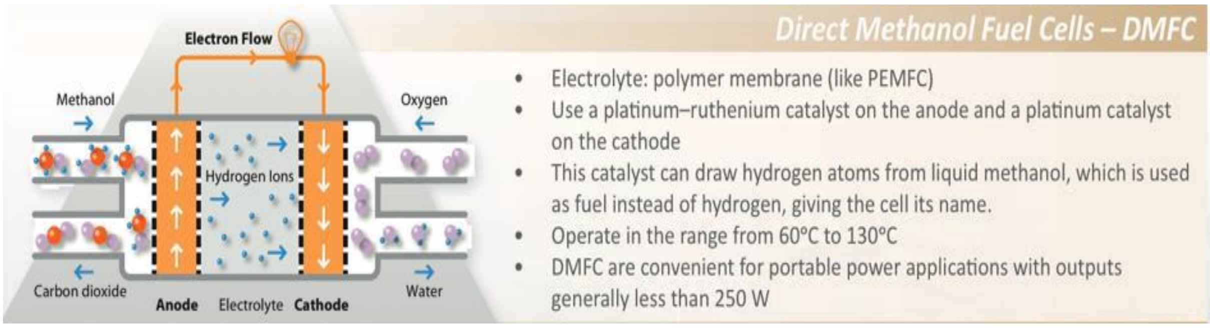

2. **Proton Exchange Membrane Fuel Cells (PEMFC)**



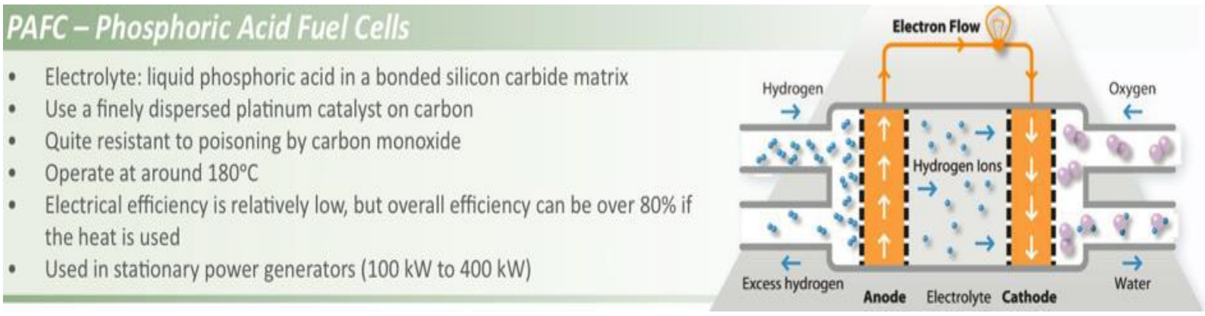

3. **Alkaline Fuel Cells**



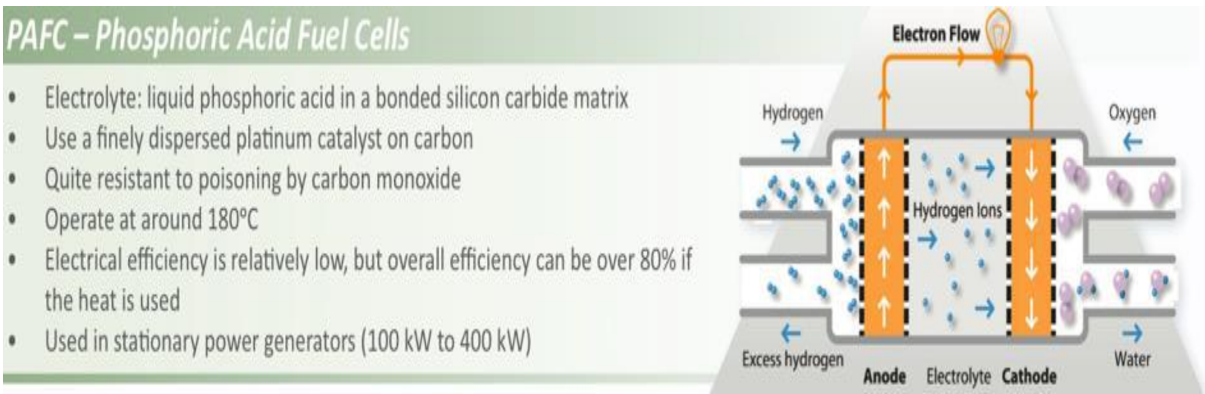

4. **Direct Methanol Fuel Cells (DMFC)**




5. **Phosphoric Acid Fuel Cells (PAFC)**




6. **Molten Carbonate Fuel Cells (MCFC)**



**The key features of the different types of electrolyser:**

| Types | Alkaline Electrolyser | PEM Electrolyser | Solid Oxide Electrolyser |
|---|---|---|---|
| **Electrolyte/Membrane** | Potassium hydroxide (KOH)/NiO | Solid, proton exchange polymer membrane (Nafion) | a) Zirconia ceramics $(0.91ZrO_2\text{-}0.09Y_2O_3)$<br>b) Zirconia Oxide ceramics |
| **Electrodes/Catalyst** | Anode: Ni/Ni alloys, metal oxides<br>Cathode: Steel + Ni / Ni-Co | Anode: Graphite-PTFE + Ti / $RuO_2$, $IrO_2$<br>Cathode: Graphite + Pt / Pt | Anode: Ceramics (Mn, La, Cr) / Ni<br>Cathode: Zr & Ni cermets / CeOx |
| **Global Reaction** | Anode: $4HO^-(aq) \rightarrow O_2(g) + 2H_2O(l) + 4e^-$<br>Cathode: $4H_2O(l) + 4e^- \rightarrow 2H_2(g) + 4HO^-(aq)$ | Anode: $6H_2O(l) \rightarrow O_2(g) + 4H_3O^+(aq) + 4e^-$<br>Cathode: $4H_3O^+(aq) + 4e^- \rightarrow 4H_2(g) + 4H_2O(l)$ | a)Cathode: $2H_2O(g) + 4e^- \rightarrow 2H_2(g) + 2O^{2-}$ Anode: $2O^{2-} \rightarrow O_2(g) + 4e^-$<br>b)Anode: $2H_2O \rightarrow 4H^+ + O_2(g) + 4e^-$ Cathode: $4H^+ + 4e^- \rightarrow 2H_2(g)$ |
| **Operational Temperature** | 50 – 100 °C | 80 – 100 °C | 800 – 1000 °C |
| **Operational Pressure** | 3 – 30 bars | 1 – 200 bars | ?? |
| **Capacity** | 10 – 200 Nm³/h $H_2$ | 0.01 – 10 Nm³/h $H_2$ | 1 – 10 Nm³/h $H_2$ |
| **Conversion Efficiency** | 75 – 95 % | 80 – 90 % | 80 – 90 % |
| **Operational Life** | 15 – 20 yrs | 15 – 17 yrs | ?? |
| **State of Development** | Marketed | Marketed | Research |

*Figure 2-43 Summary of the key features of the different types of electrolyser*

## Fuel cell stack

Fuel Cell Stack Design Principles :

A single H2/Air fuel cell has potential of about 1 V at open circuit, which decreases to 0.6–0.7 V in operation as a function of current density. In order to increase the potential to some practical levels the cells are connected in a stack. A fuel cell stack consists of a multitude of single cells stacked up so that the cathode of one cell is electrically connected to the anode of the adjacent cell. In that way exactly the same current passes through each of the cells. Note that the electrical circuit is closed with both electron current passes through solid parts of the stack (including the external circuit) and ionic current passes through electrolyte (ionomer), with the electrochemical reactions at their interfaces (catalyst layers).

A fuel cell stack is configured to power any load ranging from watts to megawatt by varying cells connected in series. During stack assembly, major emphasis must be placed on application of adequate external pressure for reducing the ohmic losses, the purpose of which is to achieve proper contact between the cell components and minimize the contact resistance. The geometries are evaluated for end plate designs with a view to understand the pressure distribution and contact resistance in each case. Among different designs, extruded hexagon is found to perform well with an average contact pressure of 0.13 MPa and contact resistance of 28 Ω-cm2. Greater gasket thickness requires higher forces to be applied before the GDL makes contact with BPP. The effect of gasket thickness mismatch is evaluated for different values to identify its appropriate value. The pressure is applied using bolts and position and number of bolts is determined for homogeneous contact pressure on the active area.

**Fuel Cell Stack Size**

The first step in engineering a fuel cell stack is to obtain the power requirements. The stack is then designed to meet those requirements, and the maximum power, voltage, and current are often known. The power output of a fuel cell stack is a product of stack voltage and current:

$$W_{FC} = V_{st} \cdot I$$

The maximum power and voltage requirements are dependent upon the application. The engineer must understand these specifications to build an appropriately-sized fuel cell stack. It is helpful to know the current and power density when designing a fuel cell stack. These are often unavailable initially but can be calculated from the desired power output, stack voltage, efficiency, and volume and weight limitations. The current is a product of the current density and the cell active area:

$$I = i * A_{cell}$$

The cell potential and the current density are related by the polarization curve:

$$V_{cell} = f(i)$$

An example of a polarization curve is shown in **Figure 2.44**. The polarization curve can be used to help initially design the fuel cell stack.

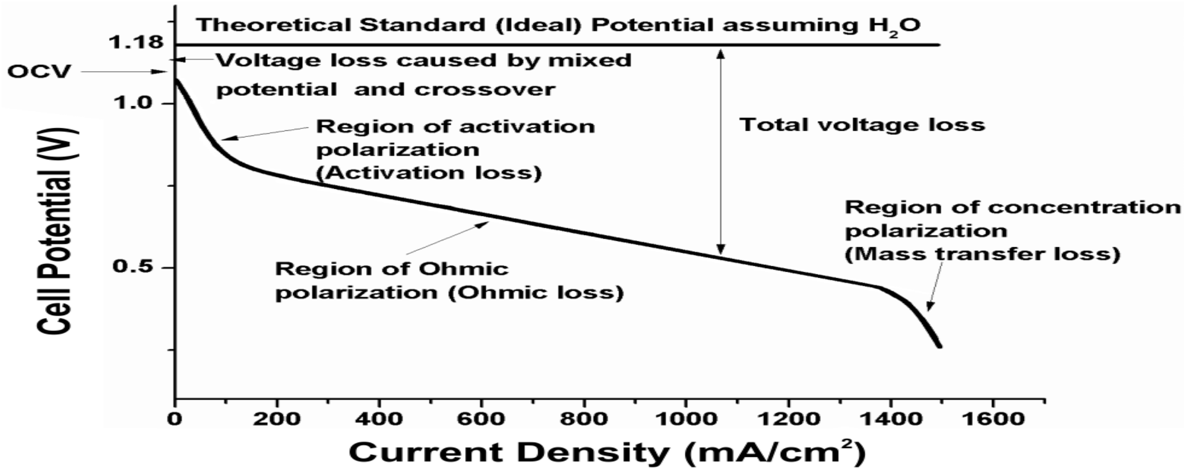



*Figure 2-44 Typical polarization curve for a PEAM fuel cell stack*

**The fuel cell stack efficiency can be approximated with the following equation:**

$$\eta_{stack} = \frac{V_{cell}}{1.482}$$

**Fuel cell system:**

In a fuel cell system, the stack is the main component but it is only one part of the whole system. The other components are often called the balance of plant (BOP). Elements such as pumps or blowers are used to circulate the air and fuel in the stack. Compressors can be used, sometimes together with intercoolers, as for internal combustion engines. To drive the pumps, blowers and compressors, electric motors are needed.

The output of a fuel cell stack is a direct current (DC) which is almost never suitable for direct connection to any load. Therefore, some kind of power conditioning is needed. What kind of device that is used depends on the need of the load. It can be a DC/DC converter or a DC/AC inverter.

Some kind of fuel storage will always be a part of the system. In the case when the fuel used is not hydrogen a fuel processing system is needed, e.x. to produce hydrogen from fossil fuels. Different control valves, pressure regulators and in most cases a controller for coordination of the system are needed. Start-up and shutdown of the fuel cell system are complex problems for the controller. In larger fuel cell systems, a cooling system is necessary. In the case of CHP systems, it is called a heat exchanger which takes care of the excess heat and uses it for another application. When using high temperature cells, the generated heat is sometimes used in fuel or air pre-heaters. In PEM fuel cells the reactant gases are often humidified.

***Energy efficiency, Power and Lifetime***

The energy efficiency from a fuel cell stack can be as high as 80%. For the total system the efficiency is lower. How high the efficiency is, depends on the amount and what kind of components that are used. For a fuel cell car engine including the whole system, the efficiency from chemical input to kinetic energy is about 30 – 40%. For comparison it should be known that in a conventional internal combustion engine the same efficiency is typically around 18 – 22%. The power drawn by the load is an important aspect for the lifetime of a fuel cell. A smoother power consumption, i.e. an even power outtake without that many peaks, is preferable. This gives a more durable fuel cell. Car engines can be used as an example to illustrate this. A normal internal combustion engine could be assumed to have a lifetime of approximately 5000 hours, in comparison with a fuel cell engine where the lifetime is around 2000 hours. This problem occurs due to the frequent speed variations during car travel as the power consumption rises during the accelerations. If the speed were more or less constant the lifetime could be increased with a factor of 10 to 20. An application where the fuel cells have better lifetime is in CHP systems of hundreds of kilo watts. In these systems the changes in output power are small which gives a longer lifetime

**Manufacturing and environment**

Most people consider fuel cells to be an environmentally benign energy converter. That is true with some modifications. Depending on how the hydrogen fuel is produced the fuel is more or less carbon dioxide (CO2) free. If it is produced with green electricity, i.e. environmentally benign produced energy from renewable and non-polluting energy sources, the fuel is said to be clean. However, when the production uses electricity from fossil fuels such as coal, oil and natural gas there will be emissions to the atmosphere. An aspect that is seldom thought of is the manufacture of the cell. The fact that the electrodes and electrolyte are made thin and that the electrode surfaces have a microstructure makes the manufacturing energy demanding. When the cells are bound together into a stack, bipolar plates could be used. These are made from good conducting materials such as graphite or stainless steel. The mining of the raw materials for the plates is energy demanding and gives air pollution and soil contamination. Another environmental problem is that platinum often is used as a catalyst for the electrodes. Platinum is a very scarce metal and when mining, the percentage of pure platinum is very low. This leads to many different processes which are both energy demanding and polluting.

**Advantages and Drawbacks**

As all technical equipment fuel cells have both advantages and drawbacks. The different drawbacks are more or less important depending on the application and the economy of the project. A short summary of important advantages and drawbacks are listed below. The advantages are:

- Low emissions
- More efficient compared to a conventional internal combustion engine
- Simplicity, few if any moving parts
- Reliable and long-lasting system
- Silent

**The drawbacks are:**

- Lifetime
- Cost
- Hydrogen has to be produced
- Not yet available infrastructure for hydrogen

***Objectives:***

- With this this experience, students will learn how a fuel cell works
- Through this experience, students will learn how (STRUCTURE AND DESIGN OF HYDROGEN FUEL CELL )

- Through this experience, students will learn about and compare different types of fuel cells

***Experiment Components:***

Mounting frame with components

The maximum configuration of the Mounting Frame consists of the following components:

| | |
|---|---|
|  | **Fuel Cell Module**<br>The module includes the following:<br>PEM Fuel Cell Stack<br>Type: PEM fuel cell stack<br>Number of cells: 20<br>Rated power: 100W<br>Rated voltage: 12VDC<br>Reactants: Hydrogen and Air<br>Max. stack temperature: 65°C<br>Operating pressure: 0.45-0.55 Bar<br>Hydrogen purity: 99.995% dry H2<br>Flow rate at max output: 1.3 SL/min<br>Startup time: <30s<br>H2 Supply Valve<br>It controls the H2 input. When the controller turns on, also the H2 supply valve does. When system turns off, it is in the off position for preventing hydrogen leakage.<br>Purging valve<br>Excess water and hydrogen will be dispelled from the fuel cell flow channels via purge valve.<br>SCU (Short Circuit Unit)<br>It ensures best performance of the fuel cells.<br>ON<br>Is used to turn the fuel cell On and Off |
|  | **Water cup** |
| | Fuel Cell Sensor Module<br>This module includes the following:<br>Flow Meter |

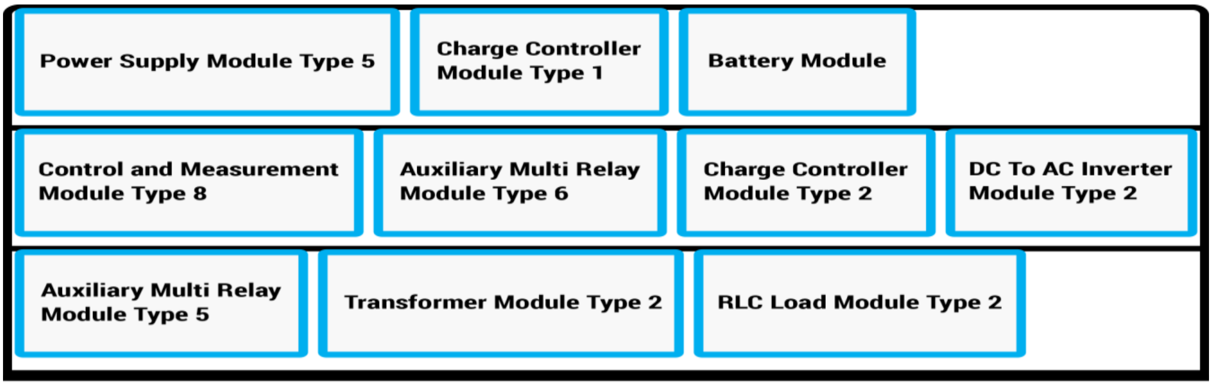
| | |
|---|---|
|  | Flow range: 0.15-15 SL/min<br>Accuracy: ±(1.5+0.5FS)%<br>Supply: 5-7VDC<br>Working Pressure: <1.5 Mpa<br>Display: Mass flow, accumulated mass flow<br>Protection: IP40<br>Pressure Transmitter<br>Range: 0-2 Bar<br>Supply: 24VDC<br>Accuracy: 0.5<br>Output: 4-20mA |
|  | **Hydrogen cylinder**<br>Material: Carbon steel<br>Pressure: 150 Bar maximum<br>Capacity: 10L<br>Weight: 15kg |
|  | **Power Supply Module**<br>This module supplies power to the other modules used in each experiment. It is switched on by a key and has short circuit protection. The input of the module is single-phase. |
|  | **Control and Measurement Module**<br>The module is based on NI myRIO platform. It combines voltage and current input, digital input/output modules. It may optionally include different software modules like Power Quality Analyzer (PQA), Microprocessor Relay Protections (MRP), Automatic Transfer Switch (ATS) and Synchronizer. This trainer includes only the PQA module. |

### *Step by Step Instructions:*

In order to start operating the following steps should be implemented:

1. Turn on the computer.

2. Place the components on the Mounting Frame with the following order:




Mounting Frame

3- After completing the appropriate wiring, please switch the power cable of the *Power Supply Module Type 5* to the power socket and switch the key of the *Power Supply Module Type 5* to turn in ON. Make sure the built-in circuit-breakers in the components are ON.

***Questions:***

1. What is the basic structure of a fuel cell?

    a. Two anodes

    b. An anode, a cathode and an electrolyte in between

    c. Two cathodes and an electrolyte in between

2. Which of the below statements is correct?

    a. the larger the electrode area is, the less time the electromechanical reaction takes

    b. the larger the electrode area is, the more time the electromechanical reaction takes

    c. the electromechanical reaction time does not depend on the electrode area

3. What types of gases are used PEM type fuel cells?

    a. Methanol and Oxygen

    b. Hydrogen and Methanol

    c. Hydrogen and Oxygen

4. Parallel connection of fuel cell stacks

    a. Increases the total output voltage

    b. increases the total output current

    c. does not affect the voltage and current

5. What is the range of energy efficiency of fuel cells?

**<u>Instructions for Preparation of Lab Report</u>**

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- YOUR Report <u>must</u> include:
    - Introduction: A brief about the experiment
    - Material and Methods/ Procedure
    - Analysis
    - Results and Discussion
    - Conclusion

The End

Introducing Recent Electrical Engineering Developments into undErgraduate cuRriculum

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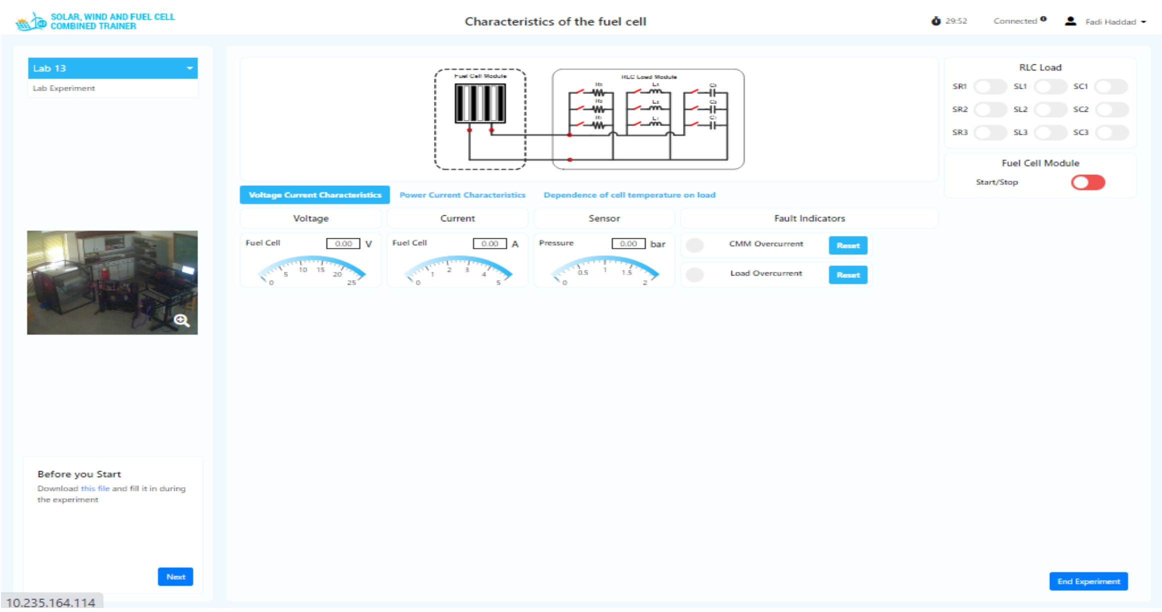
# *Power Generation Trainer Lab Sheets*

# *Exp No.11 Hydrogen Fuel Cell Trainer: Characteristics of the Fuel Cell*




*Prepared by: Walaa Al Saraireh*

*Firas Al-Adayleh*

*Reviewed by: Ziyad Altarawneh*

## 2.11 Experiment No. 11 Characteristics of the fuel cell

### *Introduction*

**ELECTROCHEMICAL PROCESSES OF ELECTROLYSIS:**

Water electrolysis is the process whereby water is split into hydrogen and oxygen through the application of electrical energy. Typically, a water electrolysis unit consists of an anode, a cathode separated with an electrolyte, and a power supply. The electrolyte can be made of an aqueous solution containing ions, a proton exchange membrane (PEM) or an oxygen ion exchange ceramic membrane. A direct current (DC) is applied from the negative terminal of the DC source to the cathode (seat of the reduction reaction), where the hydrogen is produced. At the anode, the electrons produced by the electrochemical reaction return to the positive terminal of the DC source.

An electrochemical cell involves the transfer of charge, by the movement of ions in a liquid or solid phase and the movement of electrons in a solid phase, through which electrochemical transformation of species can be achieved. An electrochemical cell is formed by placing two conducting materials (conductors or semiconductors), referred to as electrodes, into an ionically conducting electrolyte and electronically connecting them. In the cell, two sets of reactions take place at the separate electrodes, oxidations at the anode and reductions at the cathode, both of which are linked by the flow of current (Figure 2.45). This current flows in the form of electrons in the electrodes and as ions in the electrolyte, separating the electrodes.

A broad classification of electrochemical cells is based on as either Galvanic devices, which involve spontaneous reactions, or electrolysis cells, which require electrical energy input. In Galvanic cells, such as batteries or fuel cells, the chemical reactions or transformations are coupled to suitable half-cell reactions to produce a negative free energy change for the overall cell process which can then result in power production *via* electricity generation. Electrolysis cells require an applied potential field which forces the non-spontaneous electrochemical and chemical changes to occur at the electrodes. The magnitude of applied potential voltage will generally determine the rate of the charge transfer and ionic flux.

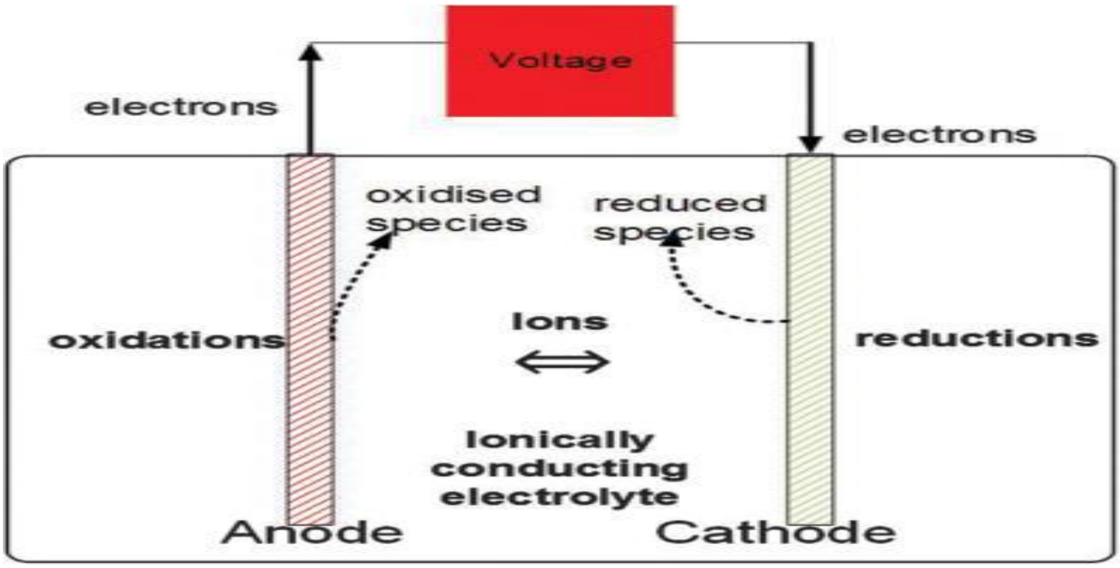



*Figure 2-45 An electrochemical cell*

In water electrolysis a voltage is applied to the cells and a DC current passes between two electrodes (see Figure 2.46), in contact with an ionic conducting medium, with hydrogen and oxygen produced by water decomposition:

$$H_2O + \text{electric energy} \rightarrow H_2 + \tfrac{1}{2}\, O_2$$

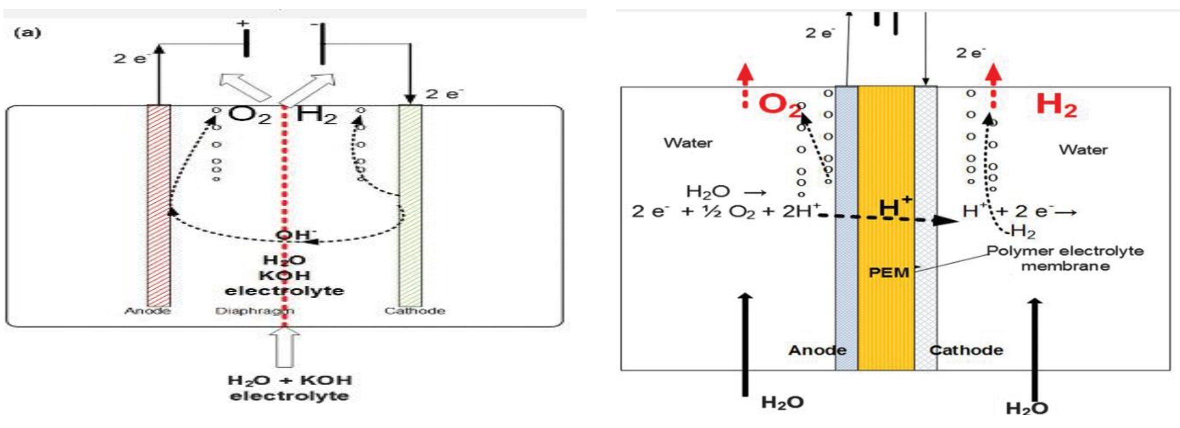



*Figure 2-46 Electrolysers for production of hydrogen from water. (a) Alkaline electrolyser (b) Solid polymer membrane electrolyser*

The individual electrode reactions that produce hydrogen, by alkaline electrolysis, at the cathode and oxygen at the anode are:

$$\textit{anode: } 2\,OH^- \rightarrow 1/2\,O_2 + H_2O + 2e^-$$

$$\textit{cathode: } 2\,H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

### *Objectives:*

- With this experiment the students will define voltage-current characteristics.
- They will learn how the voltage and the power varies based on the load.
- With this experiment the students will define power-current characteristics.
- With this experiment the students will learn how the fuel cell temperature changes from the load.

### *Experiment Components:*

**Application Software Description**

1- Fuel Cell Module ON - this button is used to turn on/off the fuel cell
2- Fuel Cell Module SCU – turns on the short circuit unit of the fuel cell
3- RLC Load Module includes:
   - SR1, SR2, SR3 switches – switches ON and OFF each stage of the Resistive load
   - SL1, SL2, SL3 switches – switches ON and OFF each stage of the Inductive load
   - SC1, SC2, SC3 switches - switches ON and OFF each stage of the Capacitive load

4- Control and Measurement Module block includes:
   - Voltage– shows the voltage value of the Fuel Cell stack
   - Current – shows the current value of the Fuel Cell stack
   - Temperature – shows the temperature of the fuel cell stack
   - Pressure - shows the hydrogen pressure at the input of the fuel cell stack

## There are three tasks in experiment No. 11

**Task 1: Voltage-current characteristics**

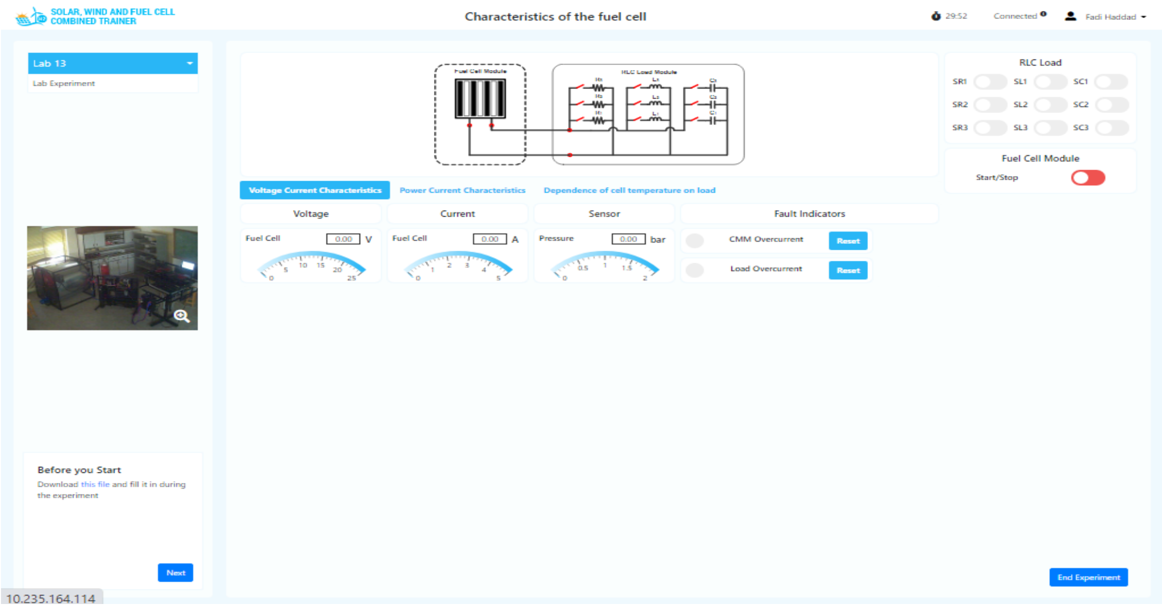



*Figure 2-47 Lab screenshot*

## Objectives:

- With this Task the students will define voltage-current characteristics.
- They will learn how the voltage varies based on the load.

## Step-by-step instructions:

1. Open Lab 13 >> Voltage-current characteristics tab in the software

If the user wants to turn On the fuel cell, but the pressure is not within 0.2-0.6Bar, then the following popup will be shown to the user.

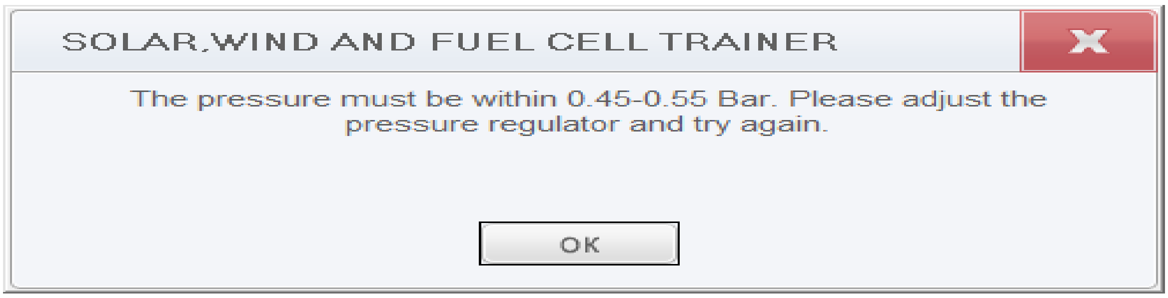



*Figure 2-48 Pressure message*

If the user wants to turn On the fuel cell, but the pressure is not within 0.2-0.6Bar, then the following popup will be shown to the user.

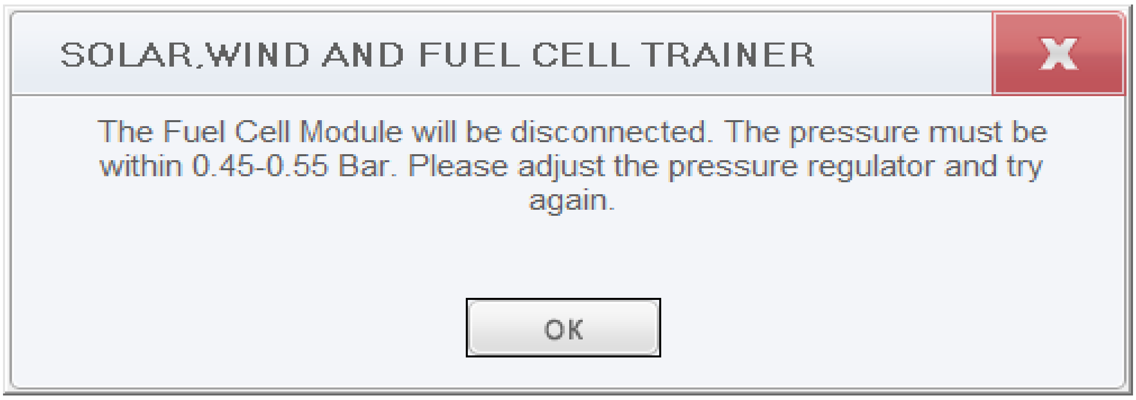



*Figure 2-49 Pressure Message during the operation*

If during the operation the pressure value drops below 0.2Bar or exceeds 0.6Bar, then the fuel cell will be turned off and the following popup will be shown to the user.

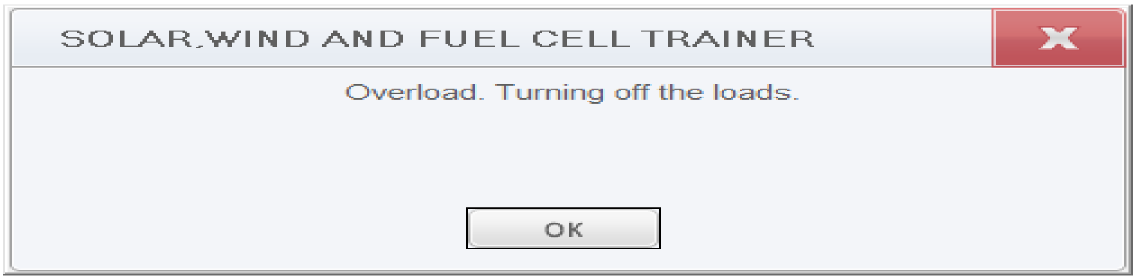



*Figure 2-50 Overload Message*

When the load exceeds the current capacity of the fuel cell, then the loads will be turned off and the following popup will be shown to the use

1- Turn on the Fuel Cell Module by pressing the ON button

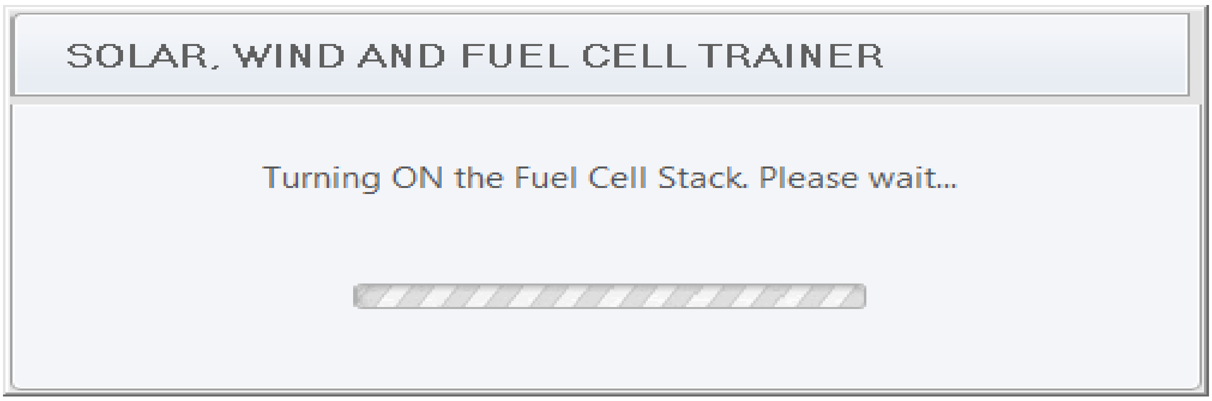



*Figure 2-51 Turn on the Fuel Cell Module*

3. After 10 seconds the stack will be running
4. Increase the load in 7 steps (turn on the switches that are mentioned in the Load Switches column and keep the rest disconnected). At each step measure the fuel cell voltage and fuel cell current. For each step wait until the voltage is stabilized before taking the measurement results. Save the results in the Table 2.14 .
5. After completing turn off the loads
6. After turning off the loads turn off the Fuel Cell Module by pressing the OFF button

*Table 2-14*

| Load | Load Switches | Voltage(V) | Current (A) |
|---|---|---|---|
| Step 1 | SR3 | | |
| Step 2 | SR2 | | |
| Step 3 | SR2, SR3 | | |
| Step 4 | SR1 | | |
| Step 5 | SR1, SR3 | | |
| Step 6 | SR1, SR2 | | |
| Step 7 | SR1, SR2, SR3 | | |

7. Draw the Voltage-Current curve using the results in the table
8. Comment on the results

### Task 2: Power-current characteristics tab

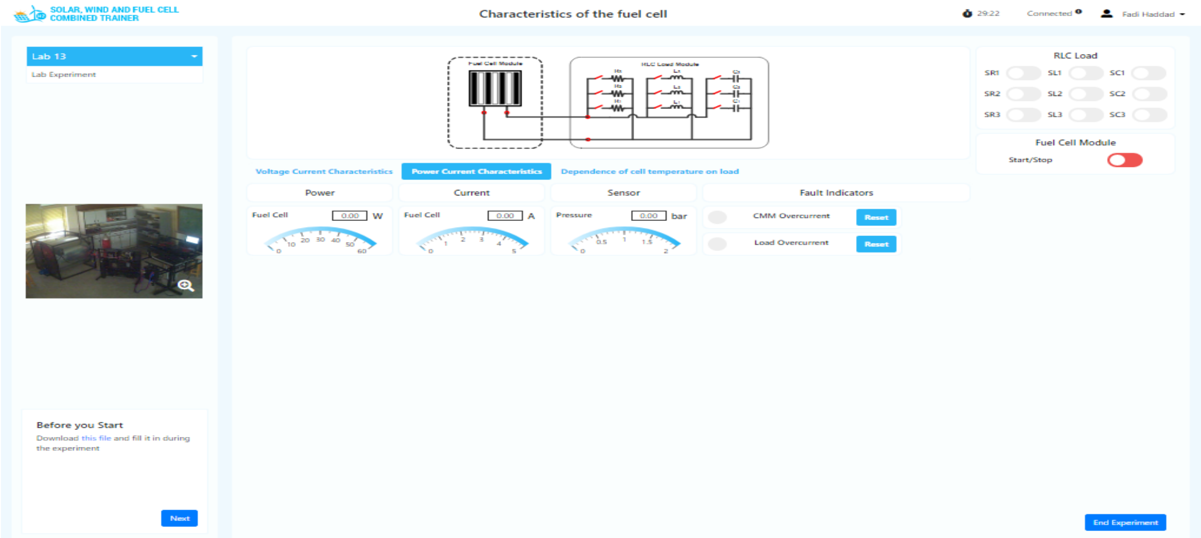



*Figure 2-52 screenshot of Lab*

## Objective:

- With this task the students will define power-current characteristics.
- They will learn how the how the power varies based on the load**.**

## Step-by-step instructions:

1. Open Lab 13 >> Power-current characteristics tab in the software
2. Turn on the Fuel Cell Module by pressing the ON button
3. After 10 seconds the stack will be running
4. Increase the load in 7 steps (turn on the switches that are mentioned in the Load Switches column and keep the rest disconnected). At each step measure the fuel cell power and fuel cell current. For each step wait until the voltage is stabilized before taking the measurement results. Save the results in the **Table 2.15**
5. After completing turn off the loads
6. After turning off the loads turn off the Fuel Cell Module by pressing the OFF button
7. Draw the Power-Current curve using the results in the table
8. Comment on the results

***NOTE**: Before implementing the next experiment, let the Fuel Cell Stack to cool down for 30 minutes.*

*Table 2-15*

| Load | Load Switches | Power (W) | Current (A) |
|---|---|---|---|
| Step 1 | SR3 | | |
| Step 2 | SR2 | | |
| Step 3 | SR2, SR3 | | |
| Step 4 | SR1 | | |
| Step 5 | SR1, SR3 | | |
| Step 6 | SR1, SR2 | | |
| Step 7 | SR1, SR2, SR3 | | |

**Task 3: Dependence of cell temperature on load**

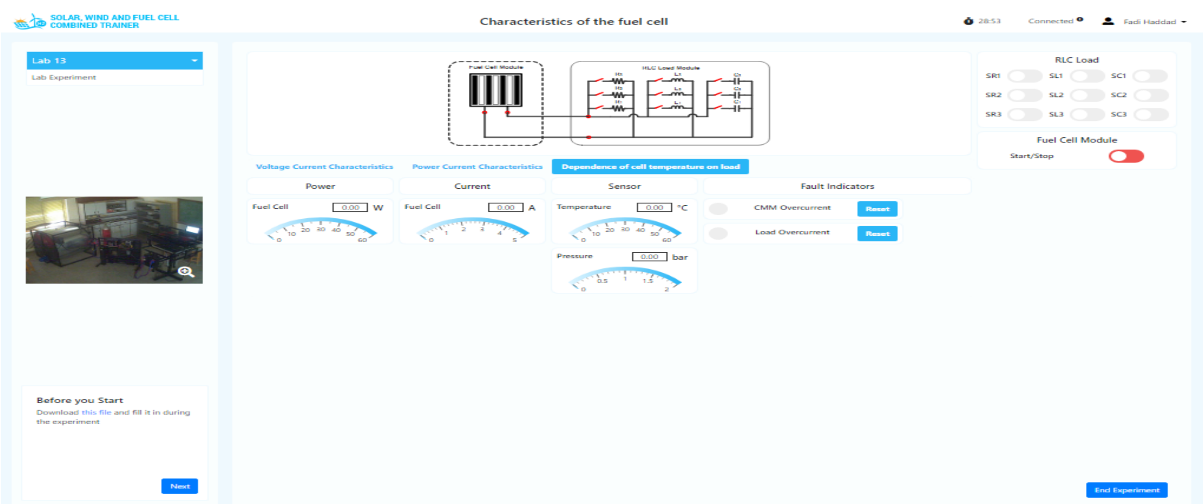



*Figure 2-53 Lab screenshot*

## Objective:

- With this task the students will learn how the fuel cell temperature changes from the load.

## Step-by-step instructions:

1. Open Lab 13>> Dependence of cell temperature on load tab
2. Turn on the Fuel Cell Module by pressing the ON button
3. After 10 seconds the stack will be running
4. Increase the load in 7 steps (turn on the switches that are mentioned in the Load Switches column and keep the rest disconnected). At each step measure the fuel cell temperature and fuel cell current. For each step wait for 8 minutes before taking the measurement results. Save the results in the Table 2.16 .
5. After completing turn off the loads
6. After turning off the loads turn off the Fuel Cell Module by pressing the OFF button
7. Draw the Temperature-Current curve using the results in the table.
8. Comment the results.

*Table 2-16*

| Load | Load Switches | Temperature (°C) | Current (A) |
|---|---|---|---|
| Step 1 | SR3 | | |
| Step 2 | SR2 | | |
| Step 3 | SR2, SR3 | | |
| Step 4 | SR1 | | |
| Step 5 | SR1, SR3 | | |
| Step 6 | SR1, SR2 | | |
| Step 7 | SR1, SR2, SR3 | | |

**Instructions for Preparation of Lab Report**

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- YOUR Report must include:
    - Introduction: A brief about the experiment
    - Material and Methods/ Procedure
    - Analysis
    - Results and Discussion
    - Conclusion

The End

## 3. PSIM Experiments

# *PSIM Experience Lab Sheets*

# *Exp No.1*
# *PSIM Guideline*

*Prepared By: Dr. Ahmad Salah*
*Reviewed by Dr. Khaled Alawasa*

## 3.1 Experiment No. 1 PSIM Guideline

### Introduction

PSIM is a simulation software specifically designed for power electronics, motor drives, and power conversion systems. With fast simulation speed and friendly user interface, PSIM provides a powerful simulation environment to meed your simulation and development needs. The PSIM simulation environment consists of the schematic program PSIM, the simulation engine, and the waveform processing program SIMVIEW2.

**PSIM runs in Microsoft Windows 10 or higher on personal computers. A minimum of 1GB RAM memory is needed**.

Renewable Energy Module library contains the following elements: Solar modules: physical model, functional model, cSi model, and thin-film model; Wind turbine; Lithium-ion and other battery models and Ultracapacitor

This experiment will briefly address these Modules and then students will use them in the followed experiments.

### Objectives

1. Familiarize students with the fundamental components of PSIM
2. Define the Renewable Energy Module library of PSIM
3. Define the solar modules Functional Model and Physical Model
4. Define the Wind Turbine and Battery Models in PSIM

### Experiment Components:

1. Solar module- Functional Model
2. Solar module -Physical Model
3. Wind turbine
4. Lithium-ion battery mode

## *Part 1: Let's Get Started with PSIM*

Figure 3.1 shows typical screen display of PSIM environment. In the figure, to illustrate as examples, PSIM elements. By default, the menu bar and the standard toolbar appear on top of the window, while the frequently used element bar appears at the bottom, and the Project View is on the left-hand side. On the right-hand side is the Design window. This is a graphic editor where users can build and editor their simulation circuit schematics. User may arrange schematics in the Design window in tiles, or in tabs.

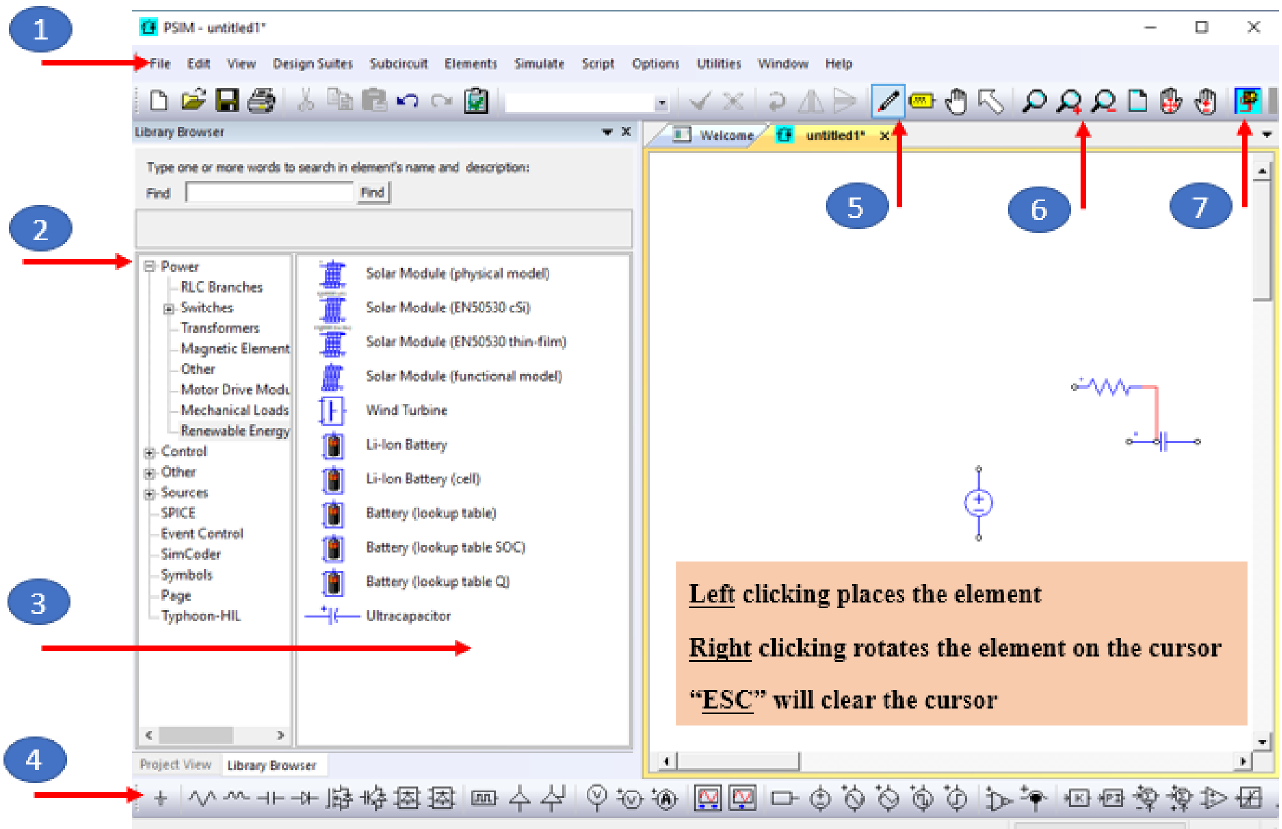



*Figure 3-1 PSIM Environment*

## Summary:

9. Place a "New Schematic" or Open saved Examples/ Schematic
10. Library Browser, all elements can be browsed or Keyword search
11. Library section (e.g., Renewable Energy elements, such as solar module, wind turbine, battery, and ultracapacitor models)
12. Element Toolbar, common elements are also on the bottom toolbar
13. Edit Menu - The wire commands
14. View Menu - Zoom In /out

15. Simulate Menu - Run PSIM simulation

## *Part 2: Solar Modules in PSIM*

These modules consist of multiple strings of solar cells, wired in series (positive to negative), and are mounted in an aluminum frame. The modules can have 60 or 72 cells in a frame. The size (area of the cells) determines the amount of amperage thus the larger the cell, the higher the amperage.

**Functional model** represents the solar module based on I-V characteristics. Functional model of solar module is easy to use because it requires only four parameters which can be obtained on any manufacturer's datasheet. Functional model does not also account for ambient temperature or light intensity changes. In Figure 3.2, the nodes marked with the "+" and "-" signs are the positive and negative terminals. The node on the top is theoretical maximum power (in W) given the operating conditions. While the positive and negative terminal nodes are power circuit nodes, the other nodes are all control circuit nodes.

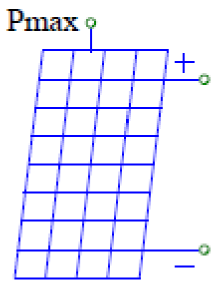



*Figure 3-2 Solar Module- Functional Model.*

Table 3.1 lists the four parameters that are required to define the behavior of functional Model. Using these four input parameters, the functional model will create the I-V and P-V curves of a typical solar cell as shown in Figure 3.3. The curves show that the solar cell output power reaches the maximum at a specific voltage level. Many control schemes have been proposed in the literature to track this maximum power point (so called Maximum Power Point Tracking, or MPPT) so that the solar cell output power is at the maximum.

*Table 3-1* Functional Model Parameters

| Parameter | Description |
|---|---|

| | |
|---|---|
| Open Circuit Voltage | Voltage measured when solar cell terminals are open circuit, in V. |
| Short Circuit Current | Current measured when the solar cell terminals are short circuited, in A. |
| Maximum Power Voltage $V_m$ | Solar cell terminal voltage when the output power is at the maximum, in V |
| Maximum Power Current $I_m$ | Solar cell terminal current when the output power is at the maximum, in A |

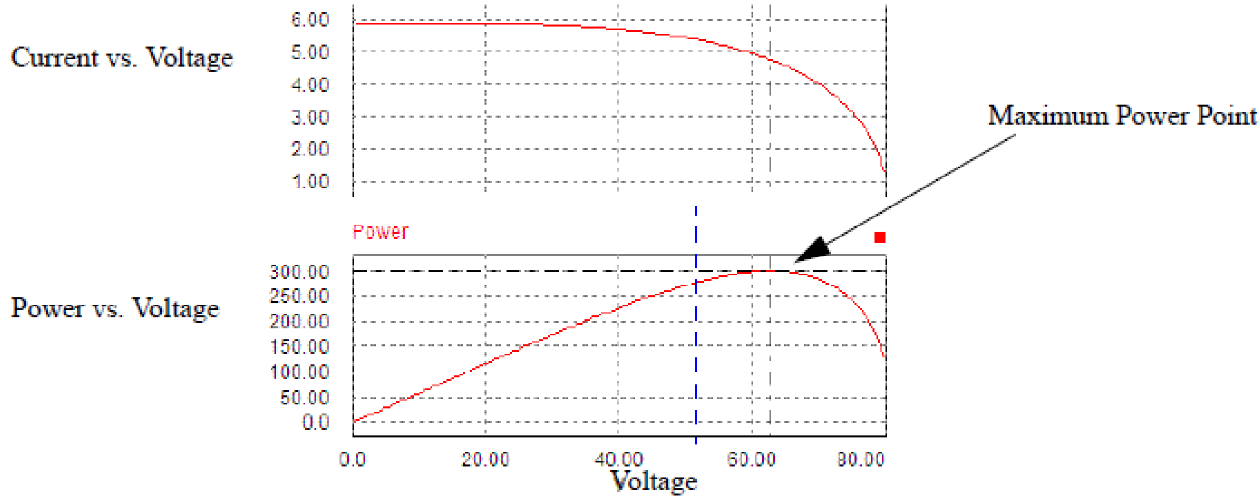



*Figure 3-3 The I-V and P-V curves of a typical solar cell.*

**The physical model** of solar module simulates the behavior of the solar module with more accuracy because it considers the light intensity and temperature variation as shown in Figure 3.4. In the image, the nodes with the "+" and "-" signs are the positive and negative terminals. The node with the letter "S" refers to the light intensity input (in $W/m^2$), and the node with the letter "T" refers to the ambient temperature input (in $^oC$). The node on the top is theoretical power (in W) given the operating conditions. While the positive and negative terminal nodes are power circuit nodes, the other nodes are all control circuit nodes.

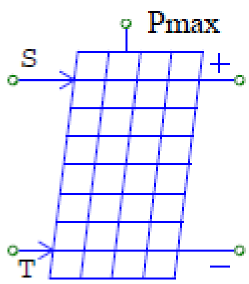



*Figure 3-4 Solar Module- Physical Mode*

Table 3.2 lists the main parameters that are required to define the physical model. A solar module consists of $N_s$ solar cells in series, and the equivalent circuit of the physical model of one solar cell is shown in Figure 3.5:

*Table 3-2 Physical Model Parameters.*

| Parameter | Description |
|---|---|
| Number of Cells $N_s$ | Number of solar cells in series in a solar module |
| Standard Light Intensity $S_0$ | Light intensity under standard test conditions, in $W/m^2$. This value is normally 1000 $W/m^2$ |
| Ref. Temperature $T_{ref}$ | Temperature under standard test conditions, in $^0C$ |
| Series Resistance $R_s$ | Series resistance of each solar cell, in Ohm. |
| Shunt Resistance $R_{sh}$ | Shunt resistance of each solar cell, in Ohm |
| Short Circuit Current $I_{sc0}$ | Short circuit current of the solar module at the reference temperature, in A. |
| Saturation Current $I_{s0}$ | Saturation current of the diode in the model, in A |
| Band Energy $E_g$ | Band energy of each solar cell, in eV |
| Ideality Factor A | Ideality factor, also called emission coefficient, of the diode in the model. |
| Temperature Coefficient $C_t$ | Temperature coefficient, in A/K |
| Coefficient $K_s$ | Coefficient that defines how light intensity affects the solar cell temperature |

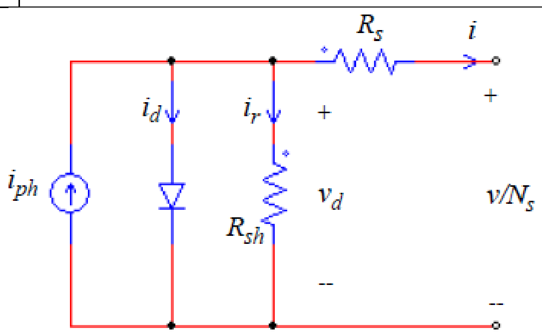



*Figure 3-5 Equivalent Circuit of the Physical Model*

The equations that describe a solar cell are:

$$i = i_{ph} - i_d - i_r$$

and

$$i_{ph} = I_{sc0} \cdot \frac{S}{S_0} + C_t \cdot (T - T_{ref})$$

$$i_d = I_0 \cdot \left( e^{\frac{qv_d}{AkT}} - 1 \right)$$

$$I_0 = I_{s0} \cdot \left( \frac{T}{T_{ref}} \right)^3 \cdot e^{\frac{qE_g}{Ak}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}$$

$$i_r = \frac{v_d}{R_{sh}}$$

$$v_d = \frac{v}{N_s} + i \cdot R_s$$

$$T = T_a + k_s \cdot S$$

where $q$ is the electron charge ($q$ = 1.6 x 10-19 C); $k$ is the Boltzmann constant ($k$ = 1.3806505 x $10^{-23}$); S is the light intensity input; $T_a$ is the ambient temperature input; $v$ is the voltage across the entire solar module; and $i$ is the current flowing out of the positive terminal of the solar module.

Some of the parameters of the physical model can be obtained from manufacturer datasheet, and the rest of the

parameters can be obtained by trial-and-error. A utility tool Solar Module (physical model) under the Utilities

menu is provided to help obtaining the parameters from manufacturer datasheet. The interface of the tool is

shown on the right.

**Task 1: Open Solar Module (physical model window) and enter the data shown in Figure 3.6 to draw an I-V curve. Then press Calculate Parameter and V-I Curve and record the results in YOUR Report.**

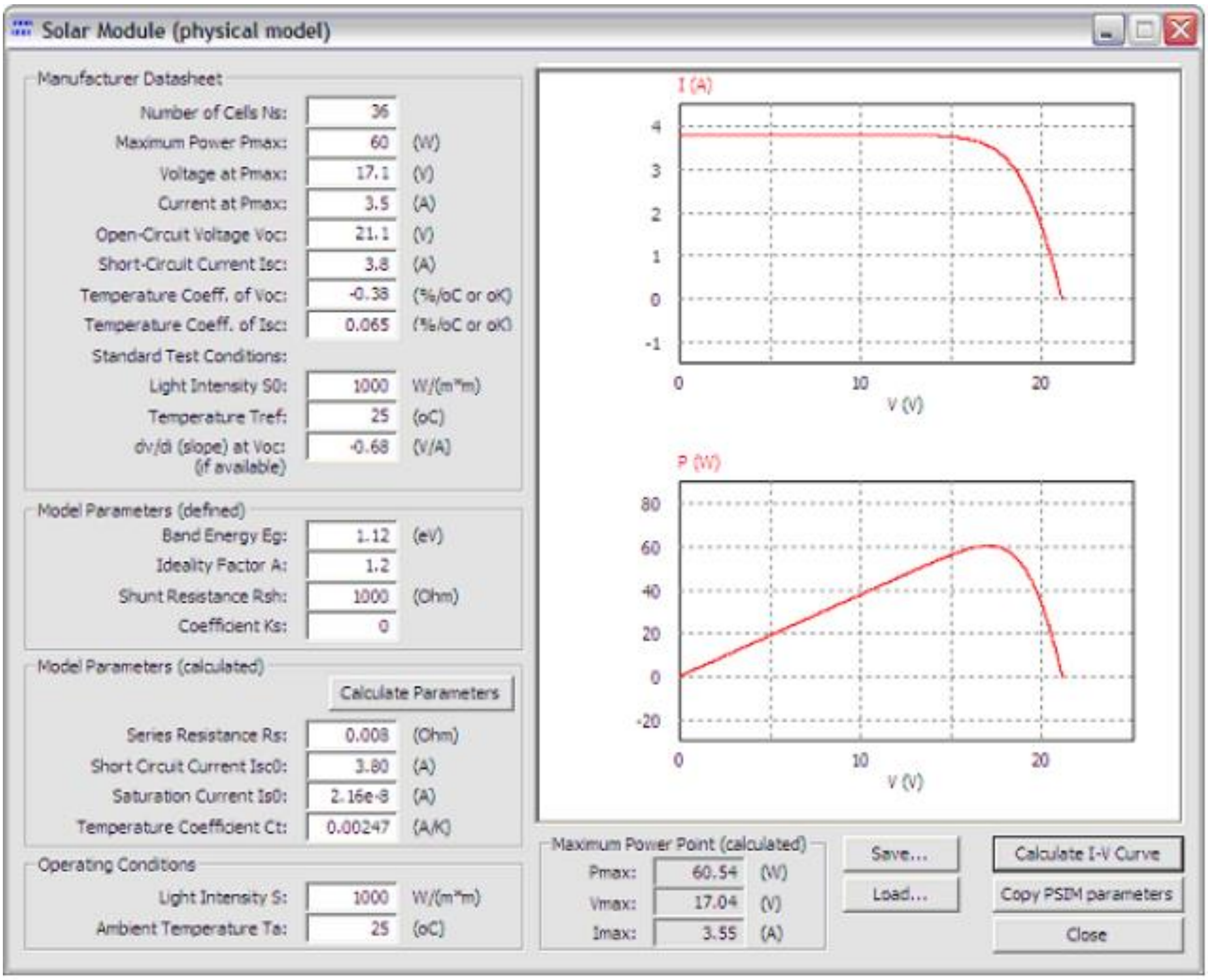



*Figure 3-6 Physical Model Window*

## *Part 3: Wind Turbine in PSIM*

Figure 3.7 describes the Wind Turbine model and the node with the letter "w" is for the wind speed input in m/s, and the node with the letter "p" is for the blade pitch angle input in deg. Both nodes are control circuit nodes. Table 3.3 lists the main parameters that are required to define the Wind Turbine.

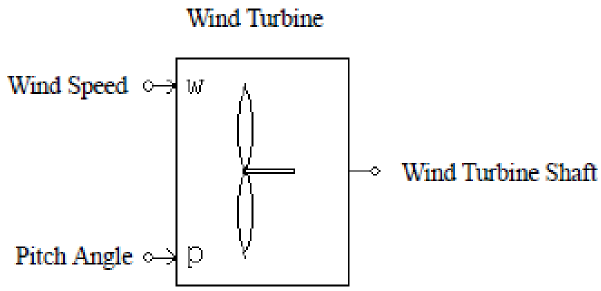



*Figure 3-7 Wind Turbine Model*

*Table 3-3 Wind Turbine Parameters.*

| Parameter | Description |
|---|---|
| Nominal Output Power | The maximum output power of the wind turbine, in W, at ⁰0 pitch angle. This power is considered as the maximum power operating point of the turbine, and it should not exceed the rated power of the generator. |
| Base Wind Speed | The base wind speed that would produce the nominal output power, in m/s |
| Base Rotational Speed | The base rotational speed of the turbine that would produce the nominal output power, in rpm |
| Initial Rotational Speed | The initial rotational speed of the turbine, in rpm |
| Moment of Inertia | Moment of inertia of the wind turbine blade, in kg*m$^2$ |
| Torque Flag | Flag to display the internal torque of the wind turbine (0: no display; 1: display) |
| Master/Slave Flag | Master/slave flag for the connected mechanical system (0: slave; 1: master) |

The power generated by a wind turbine can be expressed as:

$$P = \frac{1}{2} \cdot A \cdot v_{wind}^3 \cdot \rho \cdot C_p$$

where $A$ is the area of the rotor blade (in m$^2$), $v_{wind}$ is the wind speed (in m/sec.), $\rho$ is the air density (it is approximately 1.225 kg/m$^3$), and $C_p$ is the power coefficient. The power coefficient $C_p$ is a function of the tip

speed ratio $\lambda$ and the blade pitch angle $\beta$ and can be expressed as:

$$C_p = c_1 \cdot (c_2 - c_3\beta - c_4\beta^x - c_5) \cdot e^{-c_6} + c_7$$

where $c_1 = 0.5$, $c_2 = 116*\lambda'$, $c_3 = 0.4$, $c_4 = 0$, $c_5 = 5$, $c_6 = 21*\lambda'$, $c_7 = 0.01*\lambda$, and

$$\lambda = \frac{\omega_m \cdot R_{blade}}{v_{wind}}$$

$$\lambda' = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

where $\omega_m$ is the rotor rotational speed (in rad/sec.) and $R_{blade}$ is the radius of the rotor blade (in m).

**Task 2: The relationship between the power coefficient $C_p$ and the tip speed ratio $\lambda$ and the blade pitch angle $\beta$ can be plotted in Figure 3.8 below. Discuss this relationship according to the below figure. and record the results in YOUR Report.**

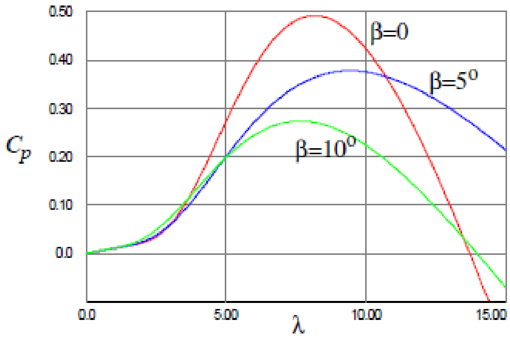



*Figure 3-8 Illustration of power coefficient C and the tip speed ratio λ and the blade pitch angle β.*

## *Part 4: Battery Models in PSIM*

PSIM provides different battery models. User may select the model according to the information available from the manufacturers of from the laboratory measurement.

A lithium-ion battery model is provided. It comes with two images: one with the battery image, and the other with the battery cell symbol image as shown in Figure 3.9. In the figure, the extra node at the top of the battery image or at the side of the battery cell symbol image is for the SOC output. It is a control circuit node. Table 3.4 also lists the main parameters that are required to define the Lithium-Ion Battery Model.


*Figure 3-9 A lithium-ion battery model*

*Table 3-4 Lithium-Ion Battery Model Parameters*

| Parameter | Description |
|---|---|
| No. of Cells in Series | Number of cells $N_s$ in series of a battery pack |
| No. of Cells in Parallel | Number of cells $N_p$ in parallel of a battery pack |
| Voltage Derating Factor | Voltage derating factor $K_s$, from 0 (100% derating) to 1 (no derating) |

| | |
|---|---|
| Capacity Derating Factor | Capacity derating factor $K_p$, from 0 (100% derating) to 1 (no derating) |
| Rated Voltage | Rated voltage $E_{rated}$ of the battery cell, in V |
| Discharge Cut-off Voltage | Battery voltage $E_{cut}$ corresponding to the maximum capacity, in V |
| Rated Capacity | Rated capacity $Q_{rated}$ of the battery cell, in Ah |
| Internal Resistance | Internal resistance $R_{battery}$ of the battery cell, in Ohm |
| Discharge Current | Discharge current of the curve under which model parameters are obtained, in A |
| Capacity Factor | Capacity factor |
| Full Voltage | Full (or maximum) voltage $E_{full}$ of the battery cell, in V |
| Exponential Point Voltage | Battery voltage $E_{top}$ at the end of the exponential region in the discharge curve, in V |
| Nominal Voltage | Battery voltage $E_{nom}$ at the end of the nominal region in the discharge curve, in V |
| Maximum Capacity | Maximum capacity $Q_{max}$ of the battery cell, in Ah |
| Exponential Point Capacity | Battery capacity $Q_{top}$ at the end of the exponential region in the discharge curve, in Ah |
| Nominal Capacity | Battery capacity $Q_{nom}$ at the end of the nominal region in the discharge curve, in Ah |
| Initial State of Charge | Initial state of charge (SOC) (from 0 to 1) |

Parameter $E_{rated}$, $E_{cut}$, and $Q_{rated}$ can be directly read from manufacturer datasheet. Some other parameters can be obtained from the battery discharge curve. A typical discharge curve is shown in the figure below (Figure 3.10).

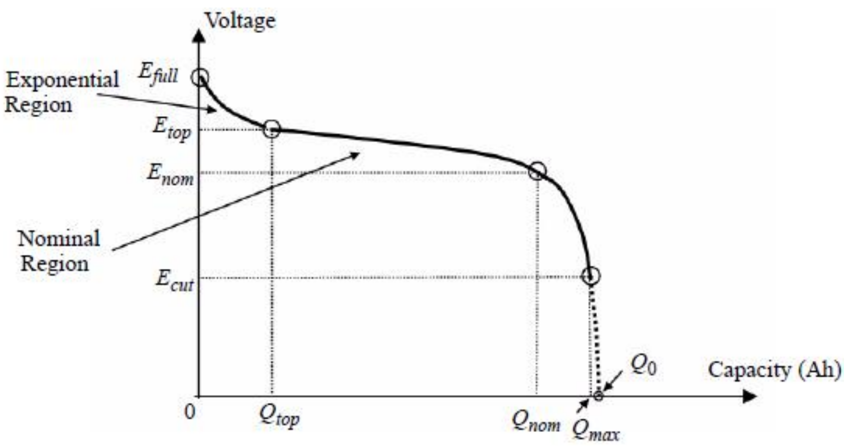



*Figure 3-10 Battery discharge curve*

**Task 3: Discuss The capacity factor according to Figure 3.9 and record the results in YOUR Report.**

Note that the battery parameters are all for one battery cell, while the model can be used to define a battery pack where the number of cells in series or in parallel is not 1. For a battery pack, all voltages need to be multiplied by *Ns*Ks*, all capacities by *Np*Kp*, and the resistance by *Ns/Np*. For example, for the entire battery pack:

$$E_{rated\_total} = N_s \cdot K_s \cdot E_{rated}$$
$$E_{cut\_total} = N_s \cdot K_s \cdot E_{cut}$$
$$E_{full\_total} = N_s \cdot K_s \cdot E_{full}$$
$$E_{top\_total} = N_s \cdot K_s \cdot E_{top}$$
$$E_{nom\_total} = N_s \cdot K_s \cdot E_{nom}$$
$$Q_{rated\_total} = N_p \cdot K_p \cdot Q_{rated}$$
$$Q_{max\_total} = N_p \cdot K_p \cdot Q_{max}$$
$$Q_{top\_total} = N_p \cdot K_p \cdot Q_{top}$$
$$Q_{nom\_total} = N_p \cdot K_p \cdot Q_{nom}$$
$$R_{battery\_total} = \frac{N_s}{N_p} \cdot R_{battery}$$

A battery model based on lookup tables is also provided in PSIM, and Table 3.5 lists the main lookup tables from manufacture datasheet to define the Lithium-Ion Battery Model. The equivalent circuit of the battery is shown in Figure 3.11.

*Table 3-5 lookup Tables- Manufacture Datasheet*

| Parameter | Description |
|---|---|
| No. of Cells in Series | Number of cells $N_s$ in series of a battery pack |
| No. of Cells in Parallel | Number of cells $N_p$ in parallel of a battery pack |
| Voltage Derating Factor | Voltage derating factor $K_s$, from 0 (100% derating) to 1 (no derating) |
| Capacity Derating Factor | Capacity derating factor $K_p$, from 0 (100% derating) to 1 (no derating) |
| Maximum Capacity | Maximum capacity $Q_{max}$ of the battery cell, in Ah |

| | |
|---|---|
| Rated Voltage | Rated voltage $E_{rated}$ of the battery cell, in V |
| Initial State of Charge | Initial state of charge (SOC) (from 0 to 1) |
| OCV-SOC Table | Table of the open circuit voltage (OCV) vs. the state of charge (SOC) |
| Rin-SOC Table (discharge) | Table of the internal resistance Rin vs. SOC during the discharge process |
| Rin-SOC Table (charge) | Table of the internal resistance Rin vs. SOC during the charge process |

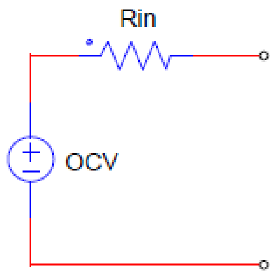



*Figure 3-11 Equivalent circuit of the battery*

For the internal resistance Rin, two tables can be defined: one during the discharge process, and another during the charge processes.

**Task 4: Follow the below steps to obtain the lookup tables from the manufacturer datasheet, then record the results.**

**Below is the procedure to obtain the lookup tables from the manufacture datasheet:**

- From the **Utilities** menu, select **Curve Capture Tool**, and capture two discharge curves of the battery voltage versus the discharge capacity from the datasheet at different discharge currents.
- Load the file "Extracting OCV and Rin_discharge.psimsch" (in "examples\batteries\lookup table"). Set the discharge currents and use the tables from the previous step. Run simulation, and display OCV and Rin_discharge separately with SOC as the x-axis variable. In SIMVIEW, select **File >> Save Display As** and save the curve to a text file. Open the file with a text editor and remove the first line. The OCV and Rin_discharge tables are ready to use by the model.
- From the **Utilities** menu, select **Curve Capture Tool**, and capture the charge curves of the battery voltage, charge current, and charge capacity versus time.
- Load the file "Extracting Rin_charge.psimsch" (in "examples\batteries\lookup table"). Use the tables from the previous step. Run simulation, and display Rin_charge with SOC as the x-axis

variable. In SIMVIEW, select **File >> Save Display** As and save the curve to a text file. Open the file with a text editor and remove the first line. The Rin_charge table is ready to use by the model.

- **Record** the results in **YOUR Report**.

## Instructions for Preparation of Lab Report

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- YOUR Report must include:
    - Introduction: A brief about the experiment
    - Material and Methods/ Procedure
    - Analysis
    - Results and Discussion
    - Conclusion

## Additional Exercises:

**will be selected by Lab instructor to provide students with different PV Module datasheet**

The End

# *PSIM Experience Lab Sheets*

# *Exp No.2 Solar Module PV Array connection*

*Prepared By: Dr. Ahmad Salah*
*Reviewed by Dr. Khaled Alawasa*

## 3.2 Experiment No. 2: PV Array connection

### Introduction

The physical model of the solar module can consider variations of the light intensity and ambient temperature. However, it requires to define input parameters. Many of these parameters can be obtained from manufacturer datasheets, while other parameters need to be obtained by trial-and-error. **PSIM** provides a utility tool called Solar Module (physical model) to define the parameters for a particular solar module. In this **LAB**, the Solar Module tool will be used to describe the main parameters of a solar module through various examples and tasks.

### Objectives

1. Define the solar module details from the datasheet.
2. Calculate parameter values $R_s$, $I_{sc0}$, $I_{s0}$, and $C_t$
3. Obtain the I-V and P-V curves, and the maximum power point.
4. Represent the solar module based on I-V characteristics.
5. Define multiple modules in Series and Parallel.

### Experiment Components:

1. Solar Modules

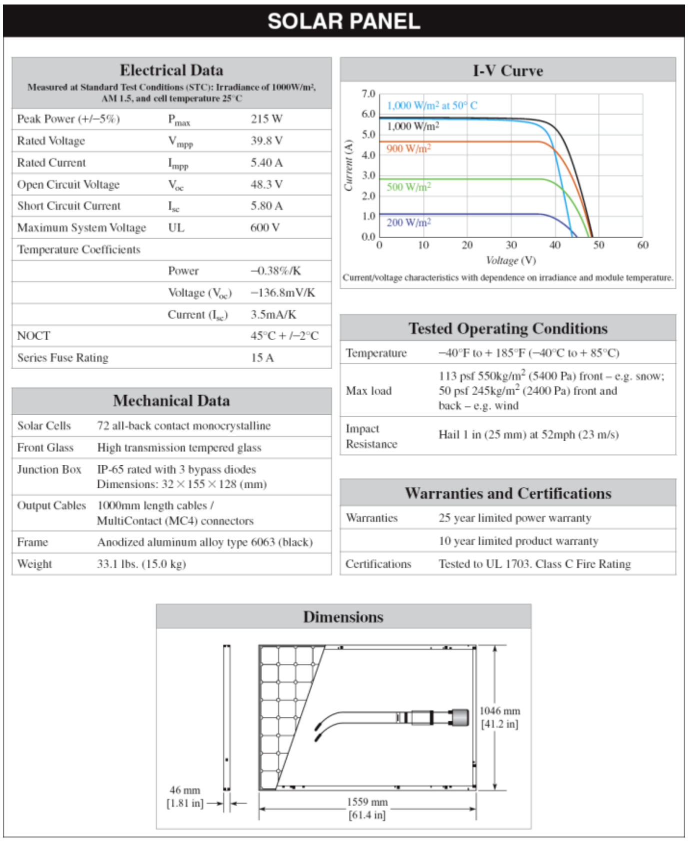
### Solar modules Datasheet: Specification & Parameters

Datasheet provides valuable information about the operating parameters of a panel that can help installers determine how to configure a solar PV system. The solar module has the following parameters, and it can also be found in the module's datasheet:

- Number of Cells $N_s$: Number of solar cells in series in a solar module
- Standard Light Intensity $S_0$: Light intensity under standard test conditions, in W/m$^2$. This value is normally 1000 W/m$^2$.
- Ref. Temperature $T_{ref}$: Temperature under standard test conditions, in $^0$C.
- Series Resistance $R_s$: Series resistance of each solar cell, in Ohm.
- Shunt Resistance $R_{sh}$: Shunt resistance of each solar cell, in Ohm

- Short Circuit Current $I_{sc0}$: Short circuit current of the solar module at the reference temperature, in A.
- Saturation Current $I_{s0}$: Saturation current of the diode in the model, in A
- Band Energy $E_g$: Band energy of each solar cell, in eV.
- Ideality Factor A: Ideality factor, also called emission coefficient, of the diode in the model.
- Temperature Coefficient $C_t$: Temperature coefficient, in A/K.
- Coefficient $K_s$: Coefficient that defines how light intensity affects the solar cell temperature.

An example of a solar module datasheet composed of wafer-type PV cells is shown in Figure 3.12.



SOLAR PANEL

**Electrical Data**

Measured at Standard Test Conditions (STC): Irradiance of 1000W/m², AM 1.5, and cell temperature 25°C

| | | |
|---|---|---|
| Peak Power (+/−5%) | $P_{max}$ | 215 W |
| Rated Voltage | $V_{mpp}$ | 39.8 V |
| Rated Current | $I_{mpp}$ | 5.40 A |
| Open Circuit Voltage | $V_{oc}$ | 48.3 V |
| Short Circuit Current | $I_{sc}$ | 5.80 A |
| Maximum System Voltage | UL | 600 V |
| Temperature Coefficients | | |
| | Power | −0.38%/K |
| | Voltage ($V_{oc}$) | −136.8mV/K |
| | Current ($I_{sc}$) | 3.5mA/K |
| NOCT | | 45°C + /−2°C |
| Series Fuse Rating | | 15 A |

**Mechanical Data**

| | |
|---|---|
| Solar Cells | 72 all-back contact monocrystalline |
| Front Glass | High transmission tempered glass |
| Junction Box | IP-65 rated with 3 bypass diodes<br>Dimensions: 32 × 155 × 128 (mm) |
| Output Cables | 1000mm length cables /<br>MultiContact (MC4) connectors |
| Frame | Anodized aluminum alloy type 6063 (black) |
| Weight | 33.1 lbs. (15.0 kg) |

**I-V Curve**



Current/voltage characteristics with dependence on irradiance and module temperature.

**Tested Operating Conditions**

| | |
|---|---|
| Temperature | −40°F to + 185°F (−40°C to + 85°C) |
| Max load | 113 psf 550kg/m² (5400 Pa) front – e.g. snow;<br>50 psf 245kg/m² (2400 Pa) front and back – e.g. wind |
| Impact Resistance | Hail 1 in (25 mm) at 52mph (23 m/s) |

**Warranties and Certifications**

| | |
|---|---|
| Warranties | 25 year limited power warranty |
| | 10 year limited product warranty |
| Certifications | Tested to UL 1703. Class C Fire Rating |

**Dimensions**



*Figure 3-12 Typical Solar Module Datasheet.*

**Task 1: According the datasheet in Figure 3.12, complete Table 3.6. Then Record the results in YOUR Report.**

*Table 3-6 Specification of the Solar Module*

| Specification | Value |
|---|---|
| Open Circuit Voltage | |
| Short Circuit Current | |
| The voltage at the maximum power point | |
| Normal Operating Cell Temperature (NOCT) | |
| The approximate power output at an irradiance of 200 W/m2? | |
| The number and the types of solar cells | |

### Solar Module Physical Model in PSIM

PSIM provides a utility tool called Solar Module (physical model) to define parameters for a particular solar module. The solar module MSX-60 from BP Solar is used to illustrate how to use the utility tool to obtain the model parameters. The process involves the following steps:

- Enter the information from the datasheet.
- Make an initial guess of certain parameters.
- Obtain the I-V and P-V curves, and the maximum power point. Compare with the datasheet and experimental data for different operating conditions, and fine tune the parameters.

**Task 2: Entering Datasheet Information.**

The figure below (Figure 3.13) shows the manufacturer datasheet image, and the region of the utility tool dialog window related to manufacturer datasheet. Your **task** is to open PSIM, then enter the required information in the right field in the dialog window depend on the datasheet as shown in Figure 3.13: **Then Record the results in YOUR Report.**

**Typical Electrical Characteristics**[1]

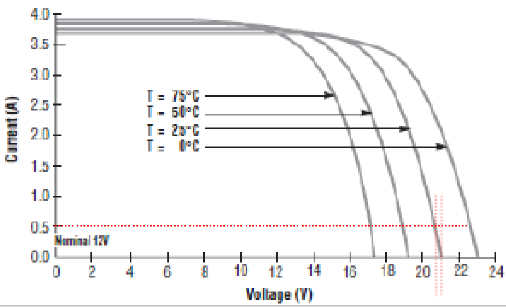
| | MSX-64 | MSX-60 |
|---|---|---|
| Maximum power (Pmax) | 64W | 60W |
| Voltage @ Pmax (Vmp) | 17.5V | 17.1V |
| Current @ Pmax (Imp) | 3.66A | 3.5A |
| Guaranteed minimum Pmax | 62W | 58W |
| Short-circuit current (Isc) | 4.0A | 3.8A |
| Open-circuit voltage (Voc) | 21.3V | 21.1V |
| Temperature coefficient of open-circuit voltage | –(80±10)mV/°C | |
| Temperature coefficient of short-circuit current | (0.065±0.015)%/°C | |
| Temperature coefficient of power | –(0.5±0.05)%/°C | |
| NOCT[2] | 47±2°C | |

NOTES:

(1) These modules are tested, labeled and shipped in 12V configuration. These data represent the performance of typical 12V modules as measured at their output terminals, and do not include the effect of such additional equipment as diodes and cabling. The data are based on measurements made in a solar simulator at Standard Test Conditions (STC), which are:
- illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5;
- cell temperature of 25°C or as otherwise specified (on curves).

Operating characteristics in sunlight may differ slightly. To determine the characteristics of modules in 6V configuration, divide the 12V voltage characteristics by 2 and multiply current characteristics by 2. Power values are unchanged.

(2) Under most climatic conditions, the cells in a module operate hotter than the ambient temperature. NOCT (Nominal Operating Cell Temperature) is an indicator of this temperature differential, and is the cell temperature under Standard Operating Conditions: ambient temperature of 20°C, solar irradiation of 0.8 kW/m², and wind speed of 1 m/s.




Manufacturer datasheet

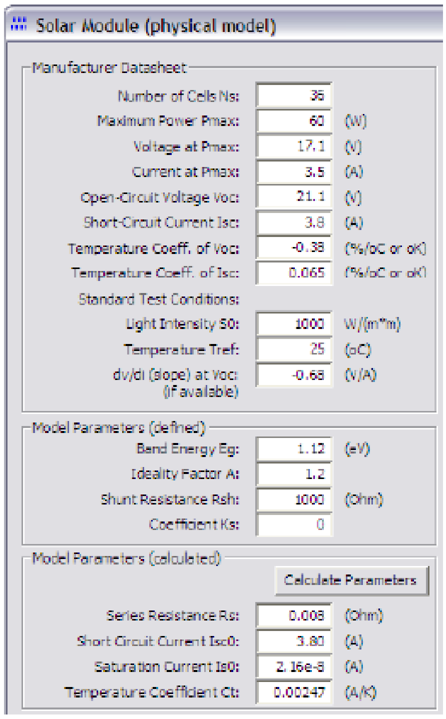



*Figure 3-13 Manufacturer datasheet and solar module window*

The value "dv/di (slope) at $V_{oc}$" refers to the dv/di slope at the open-circuit voltage $V_{oc}$ of 21.1V. From the datasheet I-V characteristics, by reading the values from the graph (marked in red dotted lines), we can calculate approximately the slope as:

$$\frac{dv}{di} = \frac{\Delta V}{\Delta i} = \frac{-0.34}{0.5} = -0.68$$

Note: If the I-V curve is not available on the datasheet, leave the dv/di value at 0.

Band energy $E_g$, ideality factor A, shunt resistance $R_{sh}$, and coefficient $K_s$ are normally not provided on the datasheet and can obtain them from manufacturers. Use the values provided below table and **Do not** close the dialog window.

| $E_g$ | A | $R_{sh}$ | $K_s$ |
|---|---|---|---|
| 1.12 | 1.2 | 1000 | 0 |

**Task 3: Calculating Parameter Values $R_s$, $I_{sc0}$, $I_{s0}$, and $C_t$.**

Based on the datasheet information, the rest of the parameters (series resistance $R_s$, short circuit current $I_{sc0}$, saturation current $I_{s0}$, and temperature coefficient $C_t$) can be calculated by clicking on the **Calculate Parameters** button. Record their values in the below table:

| $R_s$ | $I_{sc0}$ | $I_{s0}$ | $C_t$ |
|---|---|---|---|
| | | | |

**Task 4: Calculating I-V Curve.**

Under give operating conditions of the light intensity S and the ambient temperature $T_a$, one can obtain the I-V and P-V curves by clicking on the **Calculate I-V Curve** button. The calculated maximum power point will also be calculated. Define S = 1000 W/m$^2$ and $T_a$ = 25 $^o$C, and record the maximum values in the below table:

| $P_{max}$ | $I_{max}$ | $V_{max}$ |
|---|---|---|
| | | |

***Question:*** Are these values similar to the values in the datasheet? if are not, one should adjust the parameters $E_g$, A, $R_{sh}$, $K_s$, $R_s$, $I_{s0}$, and $C_t$ to obtain a better fit. **Record the results in YOUR Report.**

**Task 5: Adjusting I-V Curve.**

Change the series resistance $R_s$ to 0.008 Ohm, then click on the **Calculate I-V Curve** button. Record the maximum values in the below table and add it into **YOUR Report.**

| $P_{max}$ | $I_{max}$ | $V_{max}$ |
|---|---|---|
| | | |

The final parameter values and the I-V and P-V curves are shown in the dialog window. Take a screenshot of the dialog window and paste these curves into the below whitespace.

After the parameters are finalized, click on the **Copy PSIM Parameters** button to copy the model parameters to the PSIM schematic. To save the datasheet and parameter values to a text file to later use, click on the **Save** button, and save it to a file (for example "Solarex MSX-60.txt"). To load the data of a specific solar module back, click on the **Load** button.

### Task 6: Multiple Modules in Series.

Often several identical solar modules are connected in series to form a solar array. One can use a solar module block to model the solar array. Connecting solar panels together in series is used to increase the total system **voltage**. Figure 3.14 shows two solar modules Solarex MSX-60 connected in series, and a combined block that models two modules. The model parameters of the combined block are the same as for a single solar module, except that **the number of cells Ns is 2 times of the single solar module value.**

**Note**: when multiple modules are connected in series, a bypass diode is needed across each module if the light intensity and ambient temperature inputs are different. Also, a very small capacitor (in this case 30 nF) is needed across each module for numerical convergence.

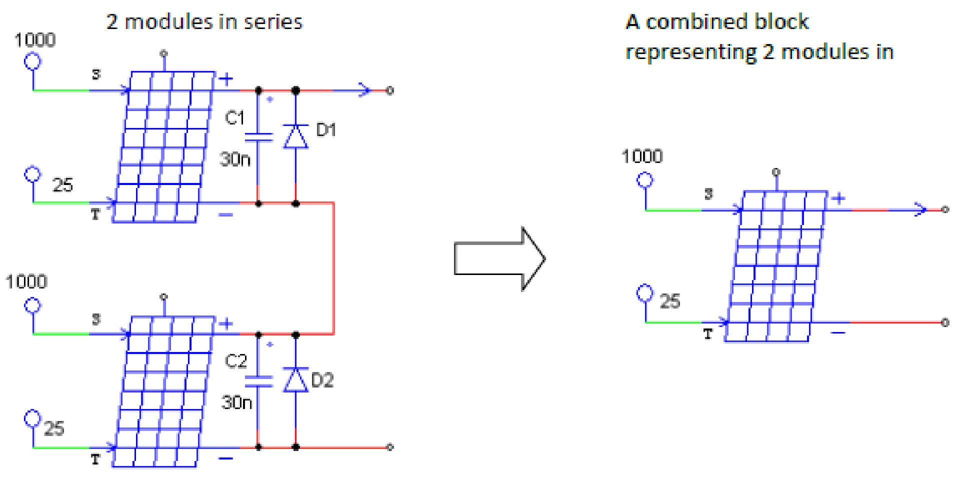



*Figure 3-14 Two modules in series and combined block*

To plot the I-V curve of the combined block, change the following quantities from the single module value:

| Number of Cells | Maximum Power | Voltage at $P_{max}$ | Open-Circuit Voltage | dv/di (slope) at $V_{oc}$ |
|---|---|---|---|---|
| $N_s$ * 2 | $P_{max}$ * 2 | Voltage at $P_{max}$ * 2 | $V_{oc}$ * 2 | dv/di (slope) at $V_{oc}$ * 2 |

Figure 3.15 shows the solar module utility tool dialog for a single module and a combined block. The parameter inputs in the red boxes **highlights** the differences. Then click on the **Calculate I-V Curve** button. Take a screenshot of the dialog window and paste these curves into **YOUR Report.**

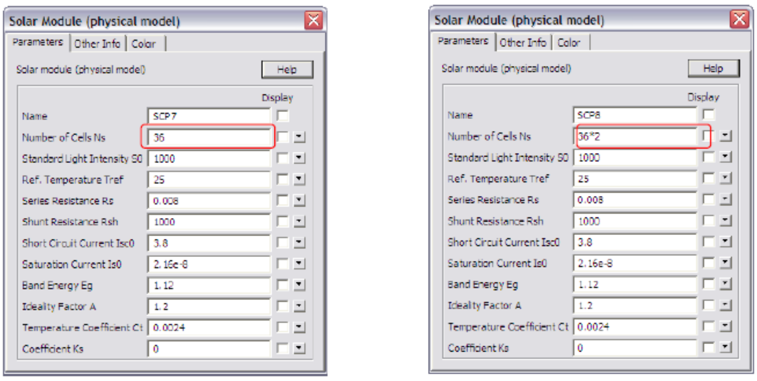



*Figure 3-15 Solar module utility tool dialog for a single module and a combined block.*

**Task 7: Multiple Modules in Parallel.**

In other cases, several identical solar modules are connected in parallel to form a solar array. One can use a solar module block to model the solar array. Connecting solar panels together in parallel is used to boost the total system current. Figure 3.16 shows two solar modules Solarex MSX-60 connected in parallel, and a combined block that models two modules. Some of the parameters of the combined block are different as compared to the parameters of a single solar module, as **highlighted** in the red boxes below in Figure 3.17.

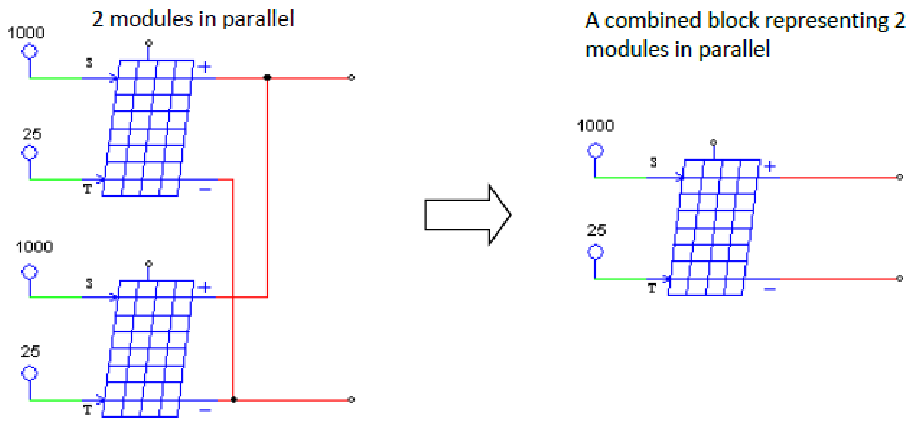



*Figure 3-16 Two modules in parallel and combined block*

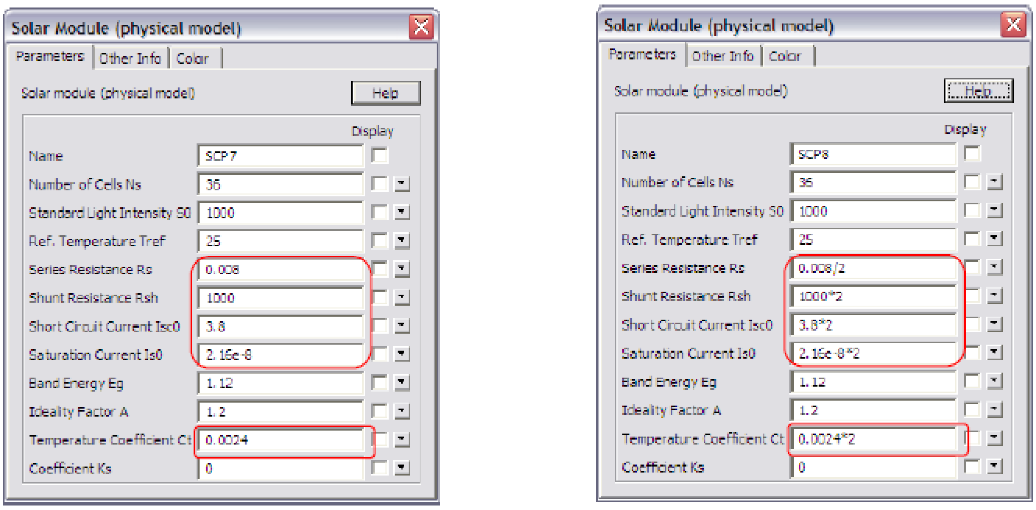



*Figure 3-17 Solar module utility tool dialog for a single module and a combined block*

To plot the I-V curve of the combined block, change the following quantities from the single module values:

| Maximum Power | Current at $P_{max}$ | Short-Circuit Current | dv/di (slope) at $V_{oc}$ | Series Resistance | Short Circuit Current | Saturation Current | Temperature Coefficient |
|---|---|---|---|---|---|---|---|
| $P_{max} * 2$ | Current at $P_{max} * 2$ | $I_{sc} * 2$ | dv/di (slope) at $V_{oc} * 0.5$ | $R_s$*0.5 | $I_{sc0} * 2$ | $I_{s0} * 2$ | Ct * 2 |

Then click on the **Calculate I-V Curve** button. Take a screenshot of the dialog window and paste these curves into **YOUR Report.**

## Instructions for Preparation of Lab Report

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- **YOUR Report** must include:
    - Introduction: A brief about the experiment
    - Material and Methods/ Procedure
    - Analysis
    - Results and Discussion
    - Conclusion

## Additional Exercises:

**will be selected by Lab instructor to provide students with different PV Module datasheet**

The End

# PSIM Experience Lab Sheets

# Exp No.3 Lithium-Ion Battery Model

*Prepared By: Dr. Ahmad Salah*
*Reviewed by Dr. Khaled Alawasa*

## 3.3 Experiment No. 3 Lithium-Ion Battery Model

### Introduction

This **LAB** describes how to use the lithium-ion battery model. Some battery model parameters can be obtained from manufacturer datasheets, while others need to be obtained by trial-and-error. This **LAB** describes how to obtain these parameters.

### Objectives

1. Define the Lithium-Ion Battery Model.
2. Define Parameters $E_{rated}$, $E_{cut}$, and $Q_{rated}$, from manufacturer datasheet
3. Calculate parameter values from the discharge curve.

### Experiment Components:

1. Lithium-Ion Battery Model

**Lithium-Ion Battery Datasheet: Specification & Parameters**

The parameters needed by the model are listed in Table 3.7:

*Table 3-7 parameters of the Lithium-Ion Battery Model*

| Symbol | Description |
|---|---|
| $Ns$ | No. of Cells in Series |
| $Np$ | No. of Cells in Parallel |
| $K_s$ | Voltage Derating Factor |
| $K_p$ | Capacity Derating Factor |
| $E_{rated}$ | Rated Voltage, in V |
| $E_{cut}$ | Discharge Cut-off Voltage, in V |
| $Q_{rated}$ | Rated Capacity, in Ah (ampere-hour) |
| $R_{batt}$ | Internal Resistance, in Ohm |
| $I_{dischg}$ | Discharge current of the curve under which model parameters are obtained, in A |
| $Kc$ | Capacity Factor |
| $E_{full}$ | Full (or maximum) battery voltage, in V |
| $E_{top}$ | Exponential Point Voltage (voltage at the end of the exponential zone), in V |

| | |
|---|---|
| $E_{nom}$ | Nominal Voltage, in V |
| $Q_{max}$ | Maximum capacity corresponding to the discharge cut-off voltage $E_{cut}$, in Ah |
| $Q_{top}$ | Exponential point capacity (capacity at the end of the exponential zone), in Ah |
| $Q_{nom}$ | Nominal Capacity, in Ah |
| SOC | Initial State of Charge |

Parameters $E_{rated}$, $E_{cut}$, and $Q_{rated}$, can be directly read from manufacturer datasheet. Some other parameters can be obtained from the battery discharge curve. A typical discharge curve is shown in Figure 3.18.

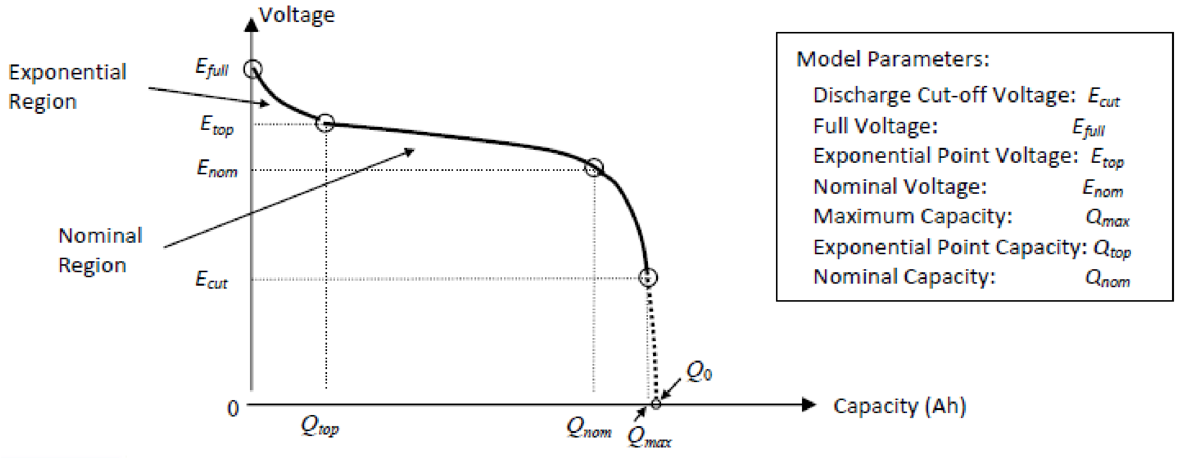



*Figure 3-18 Typical battery discharge curve*

From a specific discharge curve, one can read values of $E_{full}$, $E_{top}$, $E_{nom}$, $Q_{top}$, $Q_{nom}$, and $Q_{max}$. Note that the values of $E_{top}$, $Q_{top}$, $E_{nom}$, and $Q_{nom}$ are not exact as the transition points are often not defined exactly. One may try different values to obtain a better fit of the model characteristics to the actual characteristics. The capacity factor is roughly the ratio between $Q_0$ (the capacity at 0V) and $Q_{max}$. It is a value close to 1, and it needs to be adjusted such that the battery voltage is equal to $E_{cut}$ when SOC=0. For parameters that are not provided in the datasheet, one may ask manufacturers for the information or make an initial guess and adjust it by trial-and-error.

In this tutorial, the rechargeable **lithium-ion battery VL34570** from Saft is used to illustrate how to define the parameters to fine tune the battery model. The process involves the following steps:

- Enter the information from the datasheet.

- Make an initial guess of certain parameters from the discharge curve of the datasheet.
- Obtain the discharge and charge curves. Compare with the datasheet and experimental data for different operating conditions, and fine tune the parameters.

**Task 1: According to the datasheet in Figure 3.19, complete Table 3.8. Record the results in YOUR report.**

| | Electrical characteristics | |
|---|---|---|
| $E_{rated}$ | Nominal voltage (under 1.1 A at 20°C) | 3.7 V |
| $Q_{rated}$ | Typical capacity (under 1.1 A at 20°C 2.75 V cut-off) | 5.4 Ah |
| | **Operating conditions** | |
| | Charge method | Constant Current/Constant Voltage |
| | Maximum charge voltage | 4.20 +/- 0.05 V |
| | Maximum recommended charge current** | 5.4 A (~C rate) |
| | Charge temperature range* | - 20°C to + 60°C<br>(- 4°F to +140°F) |
| | Charge time at 20°C | To be set as a function of the charge current:<br>C rate ➡ 2 to 3 h<br>C/2 rate ➡ 3 to 4 h<br>C/5 rate ➡ 6 to 7 h |
| | Maximum continuous discharge current*** | 11 A (~2C rate) |
| | Pulse discharge current | up to 21 A (~4C rate) |
| $E_{cut}$ | Discharge cut-off voltage | 2.5 V |
| | Discharge temperature range* | - 50°C to + 60°C<br>(- 58°F to +140°F) |

*Figure 3-19 Saft VL-34570 Rechargeable lithium-ion battery electrical characteristics*

Note: The number of cells in the stack, as well as the derating factors are all set to 1 as the default.

*Table 3-8 Battery rating parameters*

| $E_{rated}$ | $Q_{rated}$ | $E_{cut}$ |
|---|---|---|
| | | |

In this case, the datasheet does not provide the battery internal resistance. One may make an initial estimate from other Lithium-Ion batteries of similar ratings. We will assume the battery internal resistance as $R_{batt}$ **= 0.065 Ohm.**

**Task 2: Estimating Parameter Values from the Discharge Curve.**

The discharge curve of the battery from the datasheet is shown in Figure 3.20. From the discharge curve, the parameters can be estimated:

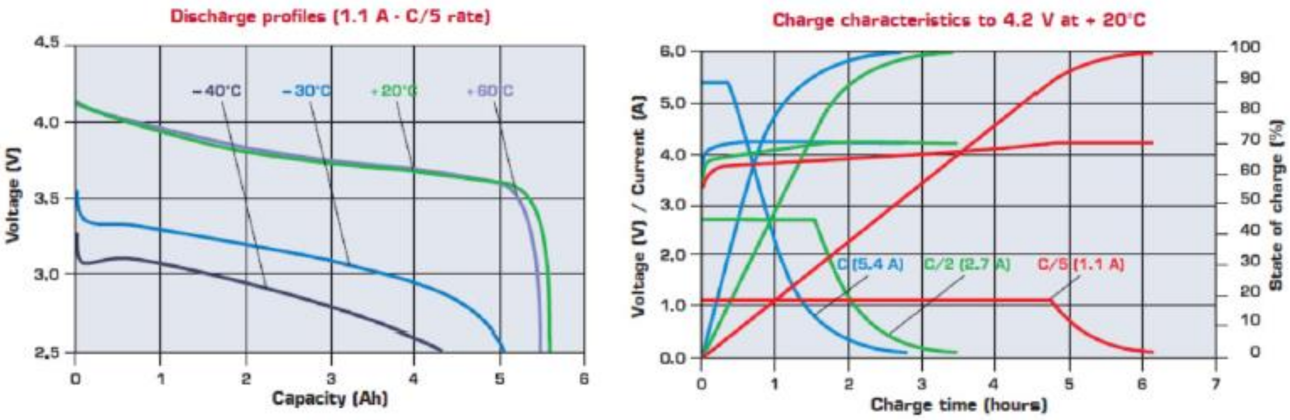



*Figure 3-20 Discharge and charge profile of the Saft VL34570 rechargeable lithium-ion battery*

**Using the +20º temperature discharge curve (1.1A), complete the initial readings of the parameters listed in Table 3.9 and add it into YOUR Report.**

The capacity factor $K_c$ is set to **1.02**. Note that except $E_{full}$ and $Q_{max}$, these values are approximate. One should adjust these parameters to better fit the simulated curves with the datasheet curves or experimental results.

*Table 3-9 Parameter Values from the Discharge Curve*

| $E_{full}$ | $E_{top}$ | $Q_{top}$ | $E_{nom}$ | $Q_{nom}$ | $Q_{max}$ |
|---|---|---|---|---|---|
| | | | | | |

Once the parameters are obtained, one can set up circuits to test the charging and discharging characteristics. A discharge test circuit is shown in Figure 3.21.

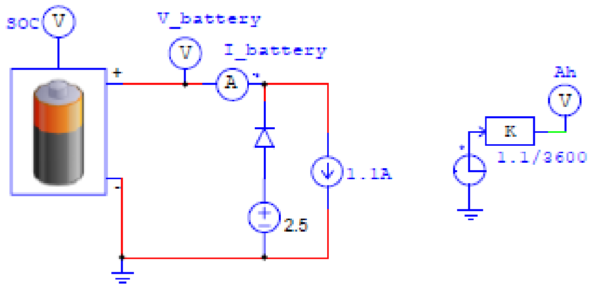



*Figure 3-21 A battery discharge test circuit*

The circuit uses a 1.1A current source to discharge the battery that has an initial state of charge of 1. The time, in sec., is divided by 3600 to convert to hour and is multiplied to the 1.1A current to obtain the capacity Ah. A charge test circuit is shown in Figure 3.22.

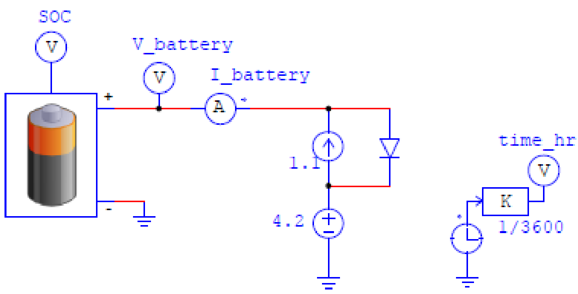



*Figure 3-22 A battery charge test circuit*

Usually, an actual battery charge circuit consists of control circuitry that regulates the charge current and battery voltage. The circuit above is an oversimplified version of a practical circuit. The charge process consists of two stages: constant-current charging and constant-voltage charging. In the initial charging stage, the charging current is limited to 1.1A. When the voltage is close to the full voltage of 4.2V, it is constant-voltage charging.

**Task 3: (a) Draw the battery charge and discharge test circuits that are shown in Figure 3.22 and Figure 3.21. (b) record the simulation results of the discharging and charging characteristics based on the initial set of parameters. Take a screenshot of the dialog window and paste into YOUR Report. (c) what can be observed from the inspection of the simulated discharge and charge curves?**

## *For Better Results*:

Some parameters may need to be adjusted to better fit the simulation curves with the datasheet curves. Here are a few ways to adjust the parameters:

- Adjust the "top" point where the exponential zone ends: For the same $Q_{top}$, the reading of the value $E_{top}$ from the datasheet is approximate. A slightly higher reading would slow down the voltage change rate, especially in the beginning of the charge/discharge process.

- Adjust the "nom" point where the nominal zone ends: At the nominal voltage $E_{nom}$, the reading $Q_{nom}$ on the datasheet curve is approximate. A slightly higher reading would slow down the voltage change rate.
- Adjust the maximum capacity: The state of charge (SOC) is calculated against the maximum capacity $Q_{max}$. If the value $Q_{max}$ is estimated too high, it would result a false situation that the battery is not fully charged (SOC < 100%) when the internal battery voltage reaches the maximum value. Also, if the value $Q_{max}$ is too high, or the value $Q_{nom}$ is too low, the corner at the end of the nominal zone in the discharge curve would be more rounded. Otherwise, the corner will be sharper.
- Adjust battery internal resistance: The battery internal resistance affects the charging curve if the battery charger is constant current constant-voltage. A larger resistance would move the transition point from constant-current to constant-voltage to a lower voltage value, causing the charger to stop charging the battery before it is fully charged.

**Note that one may need a few iterations to obtain a good fit to the datasheet or experimental results.**

## Instructions for Preparation of Lab Report

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- **YOUR Report** must include:
  - Introduction: A brief about the experiment
  - Material and Methods/ Procedure
  - Analysis
  - Results and Discussion
  - Conclusion

## Additional Exercises:

**will be selected by Lab instructor to provide students with different PV Module datasheet**

The End

*PSIM Experience Lab Sheets*

# *Exp No.4 Ultracapacitor Model*

*Prepared By: Dr. Ahmad Salah*
*Reviewed by Dr. Khaled Alawasa*

## 3.4 Experiment No. 4 Ultracapacitor Model

### Introduction

This **LAB** describes the ultracapacitor model. Unlike other models that are appropriate in simulating the charge/discharge process of a ultracapacitor in a short-to-medium period (in a few minutes), this model can model the charge/discharge process in a medium-to-long period (in hundreds of minutes).

### Objectives

1. Define the Ultracapacitor Model / Tool.
2. Define the Ultracapacitor Model Parameters ($K_v$, $R_1$, $C_1$, $R_2$, $C_2$, $R_3$, $C_3$, $R_4$, and $V_{max}$)

### Experiment Components:

1. Ultracapacitor Model

### The Ultracapacitor Model Parameters:

The ultracapacitor model parameters listed in Table 3.10. The parameters are all values for one cell.

*Table 3-10 Ultracapacitor model parameters.*

| Symbol | Description |
|---|---|
| Ns | No. of Cells in Series |
| Np | No. of Cells in Parallel |
| - | Capacitance per Cell |
| $K_v$ | Coefficient |
| $R_1$, $R_2$, $R_3$, $R_4$ | Resistance |
| $C_1$, $C_2$, $C_3$ | Capacitance |
| $V_{rated}$ | Maximum Voltage |
| - | Initial Voltage |

The parameters $K_v$, $R_1$, and $C_1$ affect the short-term response (in seconds). The parameters $R_2$ and $C_2$ affect the short-to-medium term response (in minutes). The parameters $R_3$ and $C_3$ affect the medium-to-long term response (in hundreds of minutes). The parameter $R_4$ represents the losses due to capacitor self-discharge.

To determine the model parameters, information from the datasheet is needed. In addition, experimental measurement of the ultracapacitor voltage under a charging and discharging process is needed. Figure 3.23 shows the capacitor voltage $V_c$ when it is charged by a constant current $I_s$ from 0 to t3, and at t3, the charging current is removed.

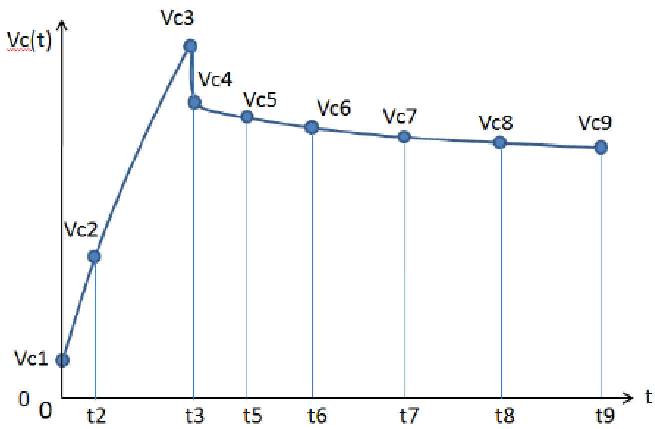



*Figure 3-23 Ultracapacitor voltage under a charging and discharging process curve*

Parameters $K_v$, $R_1$, and $C_1$ are calculated based on the charging current and the capacitor voltage at 0, t2 and t3. Parameters $R_2$ and $C_2$ are calculated based on the capacitor voltage at t3, t5, and t6. Parameters $R_3$ and $C_3$ are calculated based on the capacitor voltage at t7, t8, and t9. The parameter $R_4$ is calculated from the datasheet using the leakage current.

Given the times and voltages as highlighted in the figure above, as well as the charge current, leakage current, and rated voltage, all the model parameters can be calculated. A tool called "**Ultracapacitor Model Tool**" is provided to calculate the model parameters.

**Note** that the parameters are for a single cell. When multiple cells are connected in series or in parallel, the model automatically takes into account the multiple cell configurations.

## Ultracapacitor Model Tool

To facilitate the use of the ultracapacitor model, a parameter extraction tool called Ultracapacitor **Model Tool** is provided. It will do adjust the model parameters and do curve fitting so that simulated results match closely with the experimental data. From the Utilities menu in **PSIM**, launch the tool, and the window will appear as shown in Figure 3.24.

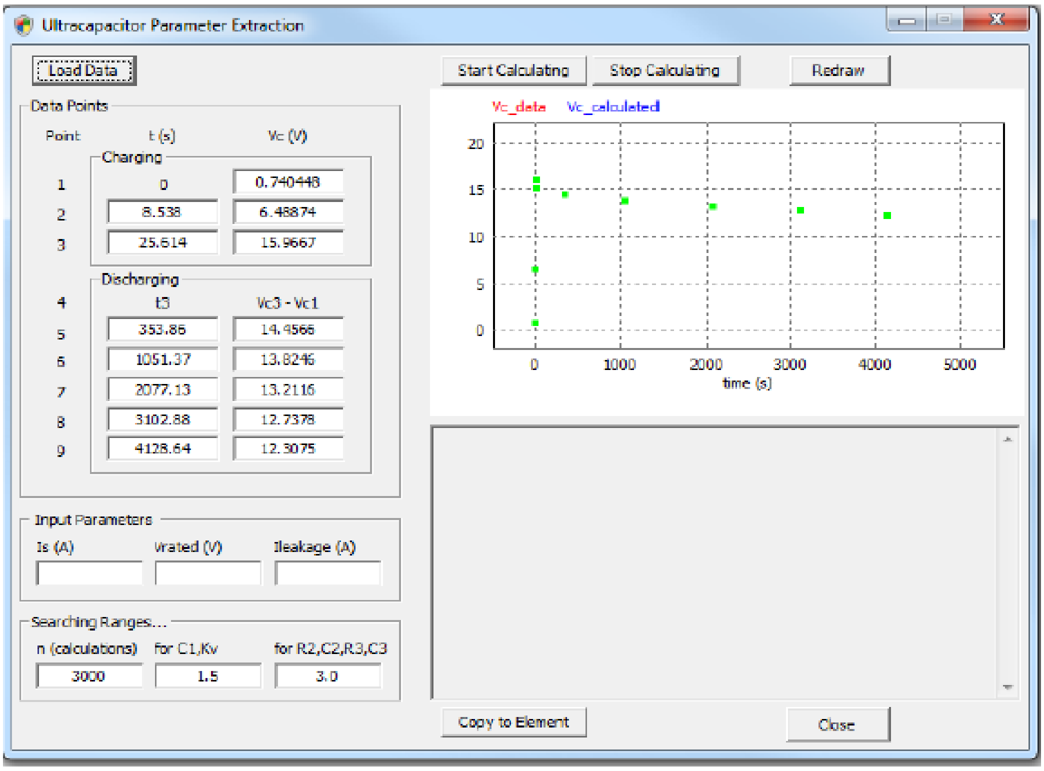



*Figure 3-24 Ultracapacitor Paraments Extraction*

**There are two ways to enter the experimental data.**

- One way is to click on the button **Load Data** and load the experimental data from a text file. The file has the following format:

| Time | Vc |
|---|---|
| 0.1 | 0.76 |
| 0.2 | 0.78 |
| 0.3 | 0.8 |

The labels in the first line "Time Vc" are optional and can be omitted. It is ok that the first data point does not start from 0. If it does not start from 0, the tool will automatically shift the time so that the first point starts from 0. Once the data is read, the tool will automatically determine the **9 points** needed to do the curve fitting, and will load into the **graph window** and will be displayed as Vc_data in red.

- Another way is to specify the 9 data points manually.

Beside the experimental data, one needs to specify the charging current Is, the rated (or maximum) voltage $V_{rated}$, and the leakage current $I_{leakage}$.

The parameters under **Searching Ranges…** define the curve fitting calculation. For example, with the default setting, the calculation will perform at most 3000 iterations, from the current solution, parameters $C_1$ and Kc will vary within 1/1.5 and 1.5 of the current solution, and parameters $R_2$, $C_2$, $R_3$, and $C_3$ will vary within 1/3 and 3 of the current solution for a new solution.

Once the data and parameters are entered, click on **Start Calculating** to start curve fitting. Results will be displayed in the window at the lower right, and calculated results will be plotted and compared with the experimental data. A key value to watch for is "Error (%)" which gives the curve fitting error.

Once satisfactory results are obtained, click on **Stop Calculating** to stop curve fitting. Record the model parameters. If the schematic of the ultracapacitor under study is open, one can copy the parameters automatically to the schematic by clicking on **Copy to Element.**

### Task 1: Solve for Maxwell Ultracapacitor 58F 16V (model BMOD0058-E016-B0).

The Maxwell 16V 58F ultracapacitor BMOD0058-E016-B0 is used. From the manufacture datasheet, the following information is obtained:

| | |
|---|---|
| Rated Capacitance: | 58F |
| Rated Voltage: | 16V |
| Leakage current at 25$^{o}$C | 25mA |

Lab experiment of a single cell capacitor is conducted with a charge current of 35A. **Load this data** into the Ultracapacitor Model Tool, with the other parameters entered, the dialog window appears as in Figure 3.25. The experimental data will be appeared in red, and the 9 selected points are in green. Click on **Start Calculating**. After less than a minute, the curve fitting error and all results will be appeared. You would stop the calculation at this point. **Take a screenshot of the dialog window and paste these curves into YOUR Report. Last Step, Record the results in the Table 3.11.**

*Table 3-11 Ultracapacitor model BMOD0058-E016-B0 paraments*

| Error (%) | $R_1$ | $C_1$ | $K_v$ | $R_2$ | $C_2$ | $R_3$ | $C_3$ | $R_4$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |

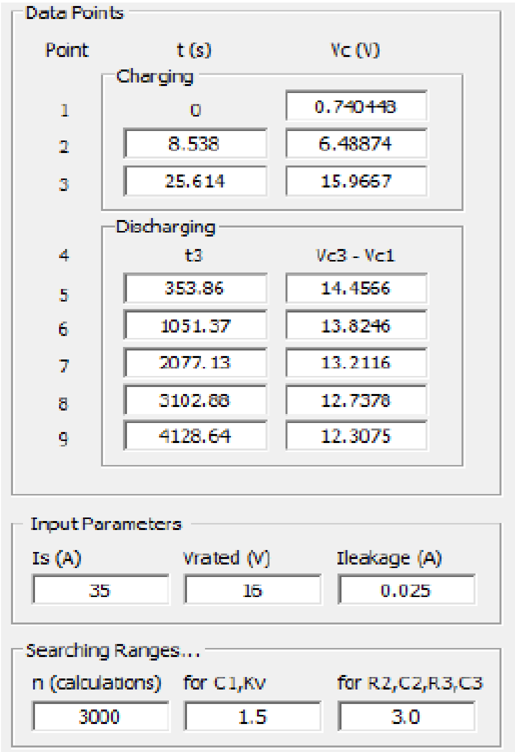



*Figure 3-25 Ultracapacitor Paraments Extraction*

## Instructions for Preparation of Lab Report

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- **YOUR Report** must include:
    - Introduction: A brief about the experiment
    - Material and Methods/ Procedure
    - Analysis
    - Results and Discussion
    - Conclusion

## Additional Exercises:

**will be selected by Lab instructor to provide students with different PV Module datasheet**

The End

# PSIM Experience Lab Sheets

# Exp No.5 Solar Module – cSi and Thin-File Models

*Prepared By: Dr. Ahmad Salah*
*Reviewed by Dr. Khaled Alawasa*

## 3.5 Experiment No. 5 cSi and Thin-File Models

### Introduction

Crystalline silicon (cSi) solar cells are currently the most popular solar cells in use mainly because c-Si is stable and efficient. There are two types of c-Si that depend on the fabrication process: monocrystalline and multicrystalline silicon. One c-Si cell generates approximately 0.5 V, and multiple cells are connected in series to raise output voltage. Thin-film solar cells are cheaper than traditional panels but less efficient.

In **PSIM**, the solar module's cSi (Crystalline Silicon) and Thin-Film models are developed according to EN50530 Standard. In this **LAB**, the cSi and Thin-File Models tool will be used to describe the main parameters of a solar module through various examples and tasks.

### Objectives

1. Define the cSi and Thin-File Models.
2. Calculate PV generator model for MPPT performance

### Experiment Components:

1. cSi Model
2. Thin-File Model

### Solar Module - cSi and Thin-File Models: Specification & Parameters

The cSi and Thin-Film models are developed according to EN50530 Standard. Only **three** parameters are needed. This is because material related data are already included in the V-I characteristic equations in these models. In Figure 3.26, the nodes marked with the "+" and "-" signs are the positive and negative terminals. The node with the letter "S" refers to the light intensity input (in $W/m^2$), and the node with the letter "T" refers to the ambient temperature input (in $^oC$). While the positive and negative terminal nodes are power circuit nodes, the other nodes are all control circuit nodes. The parameters needed by the models are listed in Table 3.12:

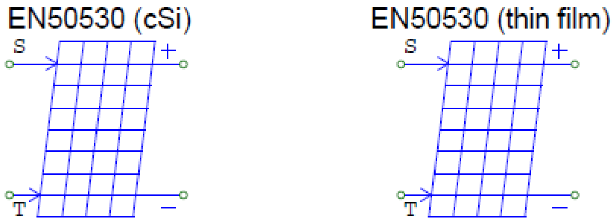



*Figure 3-26 The cSi and Thin-File Models.*

*Table 3-12 Parameter of the cSi and Thin-File Models.*

| Parameter | Description |
|---|---|
| Maximum Power | Solar cell maximum output power, in W. |
| Maximum Power Voltage | Solar cell terminal voltage when the output power is at the maximum, in V |
| Test Condition Temperature | Test condition temperature, in degree C. |

### The current-voltage characteristic of cSi and thin-film models

The current-voltage characteristic of cSi and thin-film models equations are:

$$I_{pv} = I_{ph} - I_0(e^{(Vpv + IpvRs)/(mVr)} - 1) - (V_{pv} + I_{pv}R_s)/R_p$$

Where,

$$I_0 = C_0 T_{mod}^3 e^{-\frac{Vpv}{Vr}}$$

and

$$V_T = \frac{kT_{mod}}{e_0}$$

Linear temperature model for the module temperature:

$$T_{mod} = T + \frac{c}{1000\frac{W}{m^2}}G$$

The symbols in the above equations are described in below:

| Symbol | Description |
|---|---|
| $I_{pv}$ | Module current |
| $I_0$ | Diode saturation current |
| $I_{ph}$ | Photo current (source current) |
| $V_{pv}$ | Module voltage |
| $V_t$ | Temperature voltage |
| $V_{gap}$ | bandgap |
| $R_s$ | serial resistance |
| $R_p$ | Parallel resistance |
| $T$ | Absolute ambient temperature (K) |

| | |
|---|---|
| $T_{mod}$ | Module temperature (K) |
| $G$ | Irradiance (W/m$^2$) |
| $c$ | Constant for the linear temperature model |
| $C_0$ | Coefficient of diode saturation current |
| $m$ | diode factor |
| $e_0$ | Elementary charge |
| $k$ | Boltzmann constant. |

The technology dependable parameters providing the V-I curve of this model are listed in the table below:

| | cSi | Thin Film | Tolerance |
|---|---|---|---|
| $\frac{V_{mpp}\|_{G=200(W/m^2)}}{V_{mpp}\|_{G=1000(W/m^2)}}$ | 0.95 | 0.98 | +/- 1% |
| $\frac{V_{mppSTC}}{V_{ocSTC}}$ | 0.8 | 0.72 | < 1% |
| $\frac{I_{mppSTC}}{I_{scSTC}}$ | 0.9 | 0.8 | < 1% |

**PV generator model for MPPT performance tests:**

MPP to open circuit voltage ratio:

$$FF_V = \frac{V_{mppSTC}}{V_{ocSTC}}$$

MPP to short circuit current ratio:

$$FF_I = \frac{I_{mppSTC}}{I_{scSTC}}$$

Formula for the PV current as a function of PV voltage:

$$I_{pv} = I_{sc}\left(e^{\frac{V_{pv}}{V_{oc}C_{AG}}} - 1\right)$$

Irradiance G and temperature T dependent short circuit current:

$$I_{sc} = I_{scSTC}\frac{G}{G_{STC}} \bullet [1 + \alpha \cdot (T_{pv} - T_{STC})]$$

Irradiance and temperature dependent open circuit voltage:

$$V_{OC} = V_{ocSTC} \cdot (1 + \beta \cdot (T_{pv} - T_{STC}))\left(\ln\left(\frac{G}{C_G} + 1\right) \cdot C_v - (C_R \cdot G)\right)$$

Where the temperature of the PV generator should follow the ambient conditions as follows:

$$T_{PV} = T_{amb} + T_0 + \frac{k}{1 + \tau \cdot s} \cdot G$$

The symbols in the above equations are described in below:

| Symbol | Description |
|---|---|
| $T_{PV}$ | Computed PV generator temperature |
| $T_{amb}$ | Ambient temperature |
| $T_0$ | Correction temperature ($T_0$ = -30 °C) |
| $k$ | Irradiance gain (k = 0.03 km$^2$/W) |
| τ | Time constant (τ = 5 minutes) |
| α | Temperature coefficient of the current |
| β | Temperature coefficient of the voltage |
| $C_R$, $C_V$, $C_G$ | Technology depending correction factor |

Irradiance dependent current I0 is given as:

$$I_0 = I_{scSTC}\left((1-FF_I)^{[1/(1-FF_V)]} \cdot \frac{G}{G_{STC}}\right)$$

Constant $C_{AQ}$ is given as:

$$C_{AQ} = \frac{FF_V - 1}{\ln(1-FF_I)}$$

Voltage ratio from $V_{MPP}$ at an irradiance of 200W/m2 to $V_{MPP}$ at an irradiance of 1000W/m$^2$ is given as:

$$V_{L2H} = \frac{V_{MPP}|_{G=200(W/m^2)}}{V_{MPP}|_{G=1000(W/m^2)}}$$

The parameters of the PV generator model must be set as listed in the table below:

| | cSi | Thin-Film | Tolerance |
|---|---|---|---|
| $FF_V$ | 0.8 | 0.72 | < 1% |
| $FF_I$ | 0.9 | 0.8 | < 1% |
| $C_G$ [$W/m^2$] | 2.514E-03 | 1.252E-03 | - |
| $C_V$ | 8.593E-02 | 8.419E-02 | - |
| $C_R$ [$m^2/W$] | 1.088E-04 | 1.476E-04 | - |
| $V_{L2H}$ | 0.95 | 0.98 | ±1 % |
| α | 0.04 | 0.02 | |
| β | -0.4 | -0.2 | |

**Task 1: Test Circuit of cSi Solar Cell.**

The scheme allows the cSi solar cell to be tested by adjusting the solar intensity by 200 to 1000 W/m$^2$, which means that the ratio at the maximum power point can be calculated to the above-mentioned solar intensity values. For example, the ratio $V_{mpp}(200)/V_{mpp}(1000)$=35.872/37.76=0.95, which corresponds to the parameter table shown above.

**Connect** the test circuit shown in Figure 3.27, then enter the required information in the right field in the dialog window depending on Figure 2. Then click on the **Calculate I-V Curve** button. Record the maximum values. Take a screenshot of the window of the measurement devices and paste these curves into the **Your Report**.

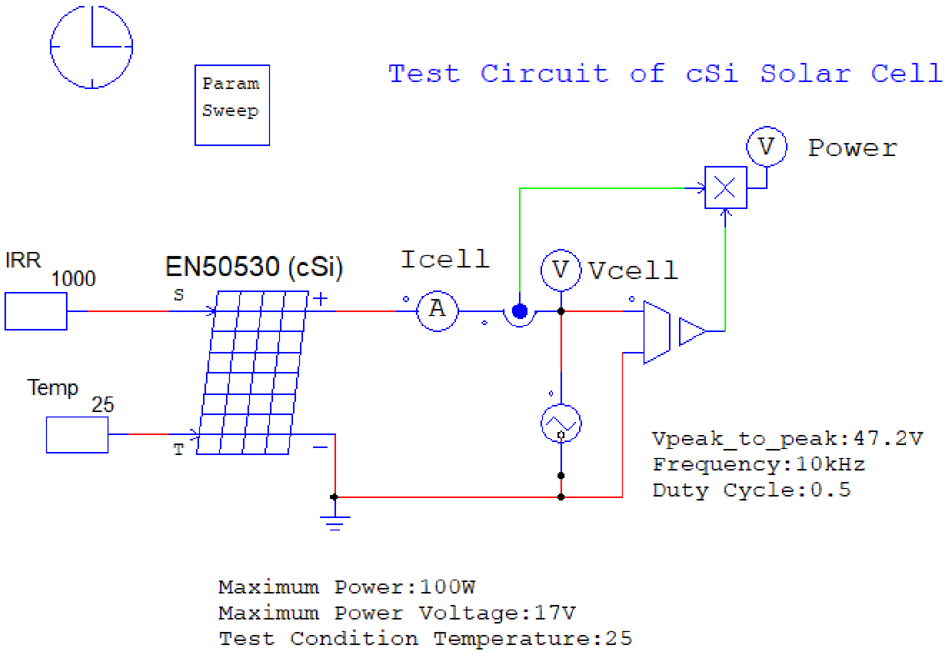



*Figure 3-27 Test Circuit of cSi Solar Cell*

## Instructions for Preparation of Lab Report

- Before preparing your report, complete the tasks and answer questions throughout the lab sheet.
- **YOUR Report** must include:
  - Introduction: A brief about the experiment
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  - Results and Discussion
  - Conclusion

## Additional Exercises:

**will be selected by Lab instructor to provide students with different PV Module datasheet**

The End