



Republic of Uzbekistan
Ministry of Higher Education, Science and Innovations

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HYBRID SOLAR POWER PLANTS

Textbook

Tashkent - 2025

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HYBRID SOLAR POWER STATIONS.

Textbook. Tashkent, 2025. – 178 pages.

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The textbook is based on a new program developed by analyzing international curricula and programs for higher education. It describes the essence of hybrid solar power plants, their operating principles, and analyzes the interrelationship of photovoltaic and thermal parameters. The relationship between electrical and energy parameters in hybrid solar power plants and concepts related to electrical and thermal energy storage are presented. Smart grids and solar hybrid systems, micropower grid structures, distributed power generation network structures, and inverter structures are analyzed.

The training manual was prepared as one of the practical results envisaged in the project "Development of a targeted training program for solar energy engineers in Uzbekistan" (101128871 - DEBSEUz - ERASMUS-EDU-2023-CBHE) within the framework of the European Union's Erasmus+ program.

The textbook was recommended for publication by the decision of the 10th meeting of the "Scientific Council" of Andijan State University held on June 3, 2025 (Protocol No. 10).

INTRODUCTION

In the last decades of the last century, renewable energy sources (RES) were among a number of priority research objects. By the 21st century, such research objects had become innovation objects of many countries. That is, the results of applied research began to turn into new types of production products. A number of important reasons can be cited for the rapid development of RES. First, the demand for energy is increasing very rapidly every year. That is, to meet the modern requirements of development, it is necessary to produce more and more electricity. However, during the period of obtaining electricity in the traditional way, that is, burning traditional energy sources in the form of solid, liquid and gaseous sources extracted from the ground, along with the depletion of natural oxygen, chemical wastes, including CO₂, polluting the environment, are released. As a result of the pollution of the Earth's atmosphere, the "Greenhouse Effect" is observed in the atmosphere, and global warming of our planet is observed. The most negative consequences of global warming are a radical change in the climate conditions of our planet, the rapid melting of glaciers, rising sea levels, the expansion of drought and desertification processes, the disruption of agricultural and horticultural systems, and the intensification of negative impacts on human health.

Therefore, great attention should be paid to the development prospects of RESs. There are many types of RESs, including thermal and photoelectric energy of sunlight, mechanical energy of wind flow, kinetic and potential energy of water flow, biological energy in the form of gases and liquids, geothermal energy sources, mechanical energy of waves and underwater currents in the seas and oceans. According to scientists from different continents of the world, the most promising type among the types of RESs is solar energy. The energy of sunlight can be converted into electrical energy in the form of thermal energy or using semiconductor photovoltaic solar cells. The energy of sunlight in both forms can be used only in open air and during the day. We cannot use solar energy effectively on sunny days and cloudy days. Therefore, even the most promising use of solar energy does not provide the opportunity to obtain energy continuously.

In this case, that is, to obtain uninterrupted electricity throughout the day, hybrid energy devices are needed. That is, an additional system that works in conjunction with the solar energy source is needed - a system that works with

another energy source. Such a system can be understood as RESs operating on wind and water flow, generators operating on liquid fuel, etc. Power plants that include such additional energy sources are called “Hybrid Solar Power Plants” (HSPs). In other words, in the training of engineering personnel in the field of HSPs, it is an urgent task to study the theoretical and practical knowledge of HSP systems, their structure, operating principles, and the parameters of the electricity obtained with their help, their mutual coordination, storage and transmission. We hope that this manual will be a direct assistant in fulfilling such an urgent task.

The manual is based on a new program developed by analyzing international curricula and programs for higher education. It describes the essence of hybrid solar power plants, their operating principles, and analyzes the interrelation of photovoltaic and thermal parameters. The concepts of the relationship between electrical and energy parameters in hybrid solar power plants and the storage of electrical and thermal energy are presented. Smart grids and solar hybrid systems, microenergy network structures, distributed energy generation network structures, and inverter structures are analyzed.

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Chapter I

SOLAR SYSTEM CHARACTERISTICS, ADVANTAGES, AND DISADVANTAGES

1.1. Solar energy and Photovoltaic panels

Solar energy is the radiant energy released by the fusion process in the nucleus of the sun (the hydrogen gas turns into helium). The intensity of solar energy outside the earth's atmosphere is approximately 1370 W/m^2 . An amount of $0\div 1100 \text{ W/m}^2$ of this energy reaches the earth because of its atmosphere. Even a small portion of this energy is many times more than the current energy consumption of humanity. The studies on the use of solar energy gained speed especially after the 1970s. Solar energy systems are technologically advanced, and their costs are decreasing. It has established itself as a clean energy source in terms of environmental impact. All of the solar radiation does not reach the earth, and up to 25 % is reflected back by the earth's atmosphere. Only 47 % of the solar radiation passes through the atmosphere and reaches the earth's surface. This energy rises the world's temperature, and lives on earth become possible. It causes wind movements and ocean fluctuations. Only 18 % of the radiation from the sun is kept in the atmosphere and clouds. Less than 1 % of the solar radiation coming from the earth is used by plants in the event of photosynthesis. All the solar radiation coming to the earth is eventually converted to heat and returned to space. The flow of energy between the atmosphere and the earth of solar radiation is given in Fig. 1.1.

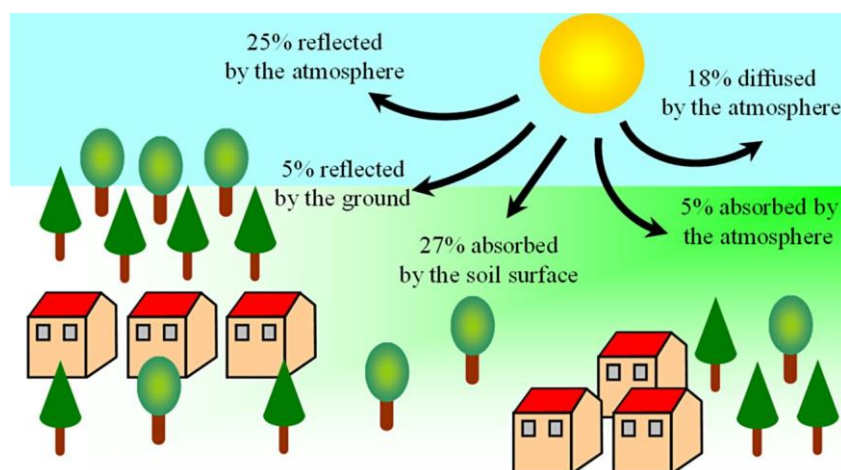


Fig. 1.1. The flow of energy between the atmosphere and the earth of solar radiation.

Solar energy is used with different technologies. The solar energy types in the indirect use method are the parabolic trough collector (PTC), linear Fresnel collector (LFC), parabolic dish collector (PDC), tower plants with central receiver power. On the basis of the previous technologies, heat is collected in a center to obtain high-rate heat. This heat energy is converted to steam, and then the electricity is obtained through the turbines. In direct use, it is converted directly into electrical energy. Solar panels are used for direct use. This technology is based on the semiconductor material base. The sunlights can be converted directly into electricity through semiconductor diodes.

Solar cells are semiconductor materials that can convert sunlight directly into their electrical energy. Solar cells, surfaces of which are square, rectangular, and circular, are generally around 100 cm^2 , and their thickness is between 0.1 and 0.4 mm. Solar cells work on the basis of the photovoltaic (PV) principle. When the light falls on them, a potential voltage occurs at their terminals. The source of the electrical energy supplied by the cell is the solar energy coming to its surface. Depending on the structure of the solar cell, PV panels can produce electrical energy in efficiency between 5 % and 30 % Fig. 1.2 shows the single crystal silicon and polycrystalline silicon solar panels made of different materials.

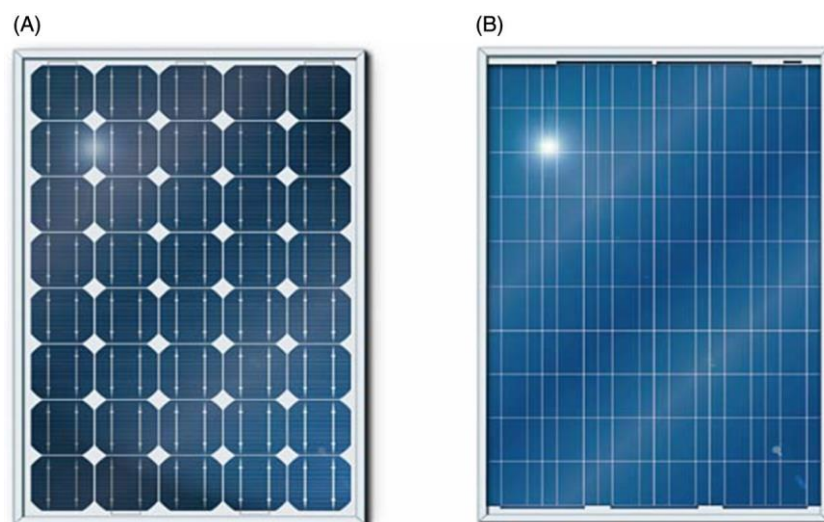


Fig. 1.2. Mono-crystalline (A) and polycrystalline silicon (B) solar panels.

In order to increase the output power, a plurality of solar cells is connected

to each other in series or in parallel. This structure is called a solar cell module or a PV module. Thus solar panels are produced at the desired current and voltage values. Depending on the power demand, from several watts to megawatts are created with the connections of the modules. Fig. 1.3 shows the sections of the PV generator process.

Solar cells can be produced using many different materials. The most widely used module technologies are thin film and crystal silicone. The a-Si, CdTe, Cu(In,Ga)S_2 , a-Si/c- μSi , and dye cells are used in the thin-film production technology. Crystalline silicon technology is mono- and multi-crystalline technology. For a 1 cm^2 cell, the highest commercially achievable cell efficiencies are Cu(In,Ga)S_2 , with a maximum of 12 % as a thin-film cell and module.

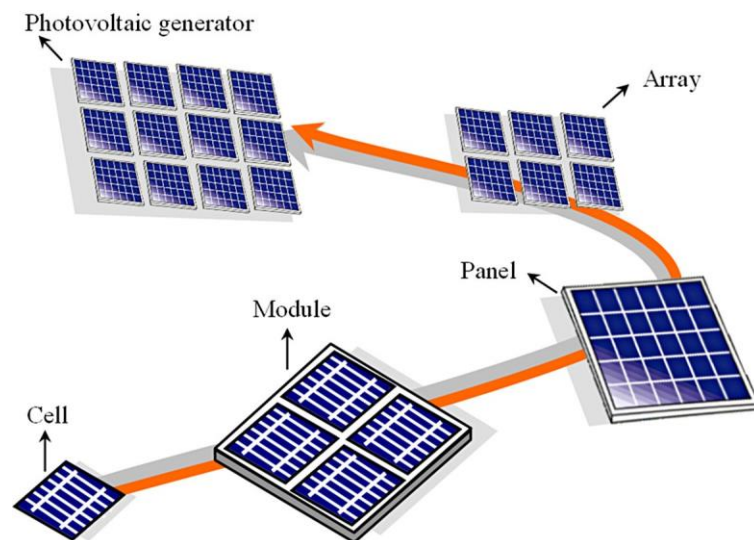


Fig. 1.3. PV generator process: 1) Element. 2) Modul. 3) Panel. 4) Massiv. 5) Fotoelektrik stansiya.

The efficiency is 22 % for a mono-crystalline silicon solar cell and is 18 % for a multi-crystalline silicon solar cell. When examined as a module, total efficiency is reduced due to the interconnection between cells and internal resistances. In terms of the PV plant production, it is approximately $12\text{--}15\text{ m}^2$ in thin-film technology as the required space per kW. When looking at the crystalline silicon PV panel, an average area of $7\text{--}8\text{ m}^2$ is needed for the same power. Commercial PV technology efficiencies are given in Table 1.1.

Table 1.1

Commercial PV technology efficiencies

PV technology	Thin film					Crystalline silicon	
	a-Si	CdTe	Ci(G)S	a-Si/□c-Si	Dyes	Mono	Multi
Cell efficiency	4 % –	10 % – 11 %	7 % – 12 %	7 % – 9 %	2 % – 4 %	16 %–22 %	14 % – 18 %
Module efficiency	8 %					13 %–19 %	11 % – 15 %
Area required for kW, ~	~15 m ²	~10 m ²	~10 m ²	~12m ²		~7 m ²	~8 m ²

1.2. Structure and operation of solar cells

In today's electronic products, transistors, rectifier diodes such as solar cells, semiconductor materials are made. Among the many substances with semiconductor properties, the most suitable for making solar cells are silicon, gallium arsenide, and cadmium telluride.

In order for semiconductor materials to be used as solar cells, negative (N)- or positive (P)-type additives are required. Additive is made by a controlled addition of the desired additives into the pure semiconductor melt. The type of semiconductors obtained depends on the additive. In order to obtain N-type semiconductor materials from the silicon used as the most common solar cell, elements such as phosphorus are used. Phosphorus in V group of the periodic table is added to the silicon melt. Since silicon has four electrons in its outer orbit and the phosphorus has five electrons in its outer orbit, the single electron of the phosphorous gives an electron to the crystal structure. Therefore V group elements are called “transmitter” or “N-type” additives.

In order to obtain P-type silicon, an element from the III group (aluminum, indium, and boron) is added to the melt. Since there are three electrons in the outer orbit of these elements, there is a lack of electrons in the crystal. The absence of this electron is called a hole or a space and is assumed to carry a positive charge. Such substances are also called “receiver” or “P-type” additives. By adding the necessary additives into the main material of type N or P, the semiconductor junctions are formed. Electrons in the N-type

semiconductor and holes in the P-type semiconductor are the main carriers. Before the N- and P-type semiconductors come together, both substances are electrically neutral. Negative energy levels and holes are equal in P-type materials, while positive energy levels and electron numbers are equal in N-type materials. When the N–P junction formed, the electrons of the N-type major carrier form a current through the P type. This event continues until the load balance occurs on both the sides. In the junction of the type N–P, a positive charge accumulates on the N side, while a negative charge on the P side.

This junction is referred to as the “transition zone” or “neutral zone.” The electric field in this region is called “structural electric field.” In order for the semiconductor junction to work as a solar cell, PV transformation in the junction region is required. This transformation takes place in two stages: first, by giving light to the junction region, electron–gap pairs are formed, and second, they are separated by the electric field in the region.

Energy conversion is based on the PV event. In the PV event, the light photons form free charge pairs, especially when they reach the junction region. Each negatively charged electron stimulated leaves a positively charged space behind. These load carriers form the natural internal inverse electric field (E_i) formed by the junction. The natural electric field activates the charge carriers that gain energy with photons. Thus negatively charged electrons produced by photons are collected in the N region, while positively charged carriers are collected in the P region to produce a voltage. The process of generating electricity of a solar cell is in principle given in Fig. 1.2.2.

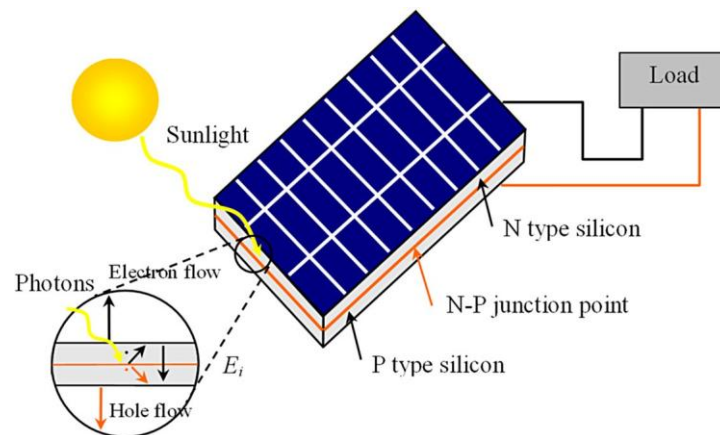


Fig. 1.2.1 Process of generating electricity of a solar cell.

The current–voltage (I–V) characteristic of a PV panel varies with the

radiation intensity (W/m^2). An example of PV panel current–output graph is given in The maximum power points that can be taken from the PV panel also vary depending on the radiation. In this case the radiation intensity directly affects the short-circuit current (I_{sc}) produced by the PV panel. The open-circuit voltage (V_{oc}) changes at a lower rate than the short-circuit current. The performance of a PV panel operating under varying radiation intensity is of great importance in PV power system designs.

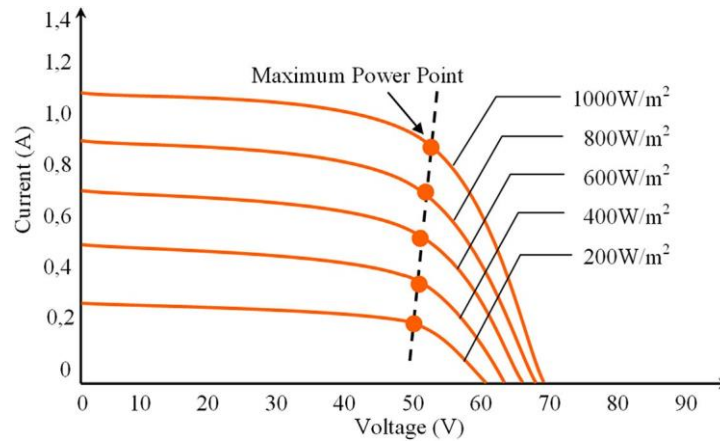


Fig. 1.2.2. Current–voltage (I–V) characteristic of a sample PV panel in different radiations.

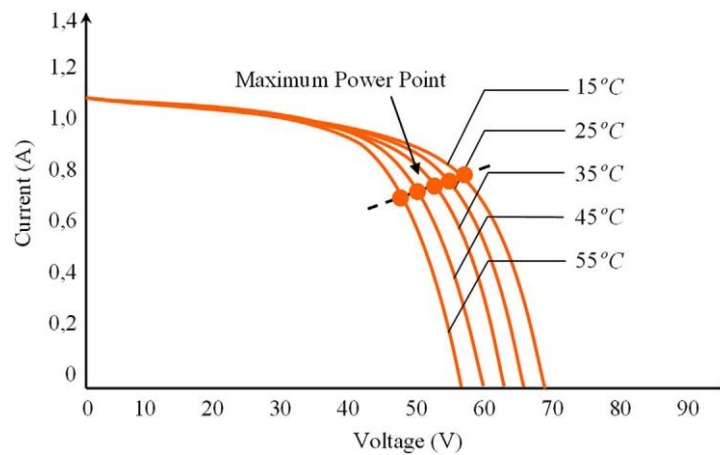


Fig. 1.2.3. Current–voltage (I–V) characteristic of a sample PV panel at different temperatures.

In addition to the effect of radiation intensity on PV panels, another important effect is the temperature. At a given temperature, the short-circuit current of the PV panel increases in proportion to the amount of radiation. Under constant radiation, the increase of temperature causes the short-circuit

current to increase and the open-circuit voltage decreases. The effect of temperature to an example PV panel is shown in Fig. 1.2.4.

Fig. 1.2.5. shows the characteristic curve of a sample PV panel at a temperature of 25 °C and a radiation rating of 1000 W/m². The maximum power point is the maximum power that can be received from a PV panel. This point is equal to the multiplication of current and voltage values of the PV panel.

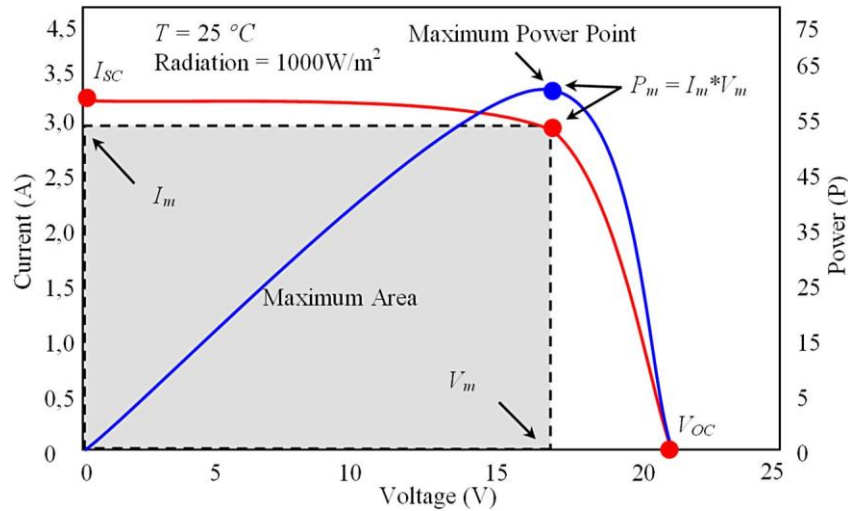


Fig. 1.2.4. Current–voltage–power (I–V–P) characteristic of a sample PV panel.

The maximum rectangular area below the I–V curve gives the maximum power (P_m) that the PV panel currently produces. The current in this power is indicated by I_m , and the voltage is by V_m . When the PV panel terminals are open, the measured voltage is the highest voltage value of the PV panel and is indicated by V_{si} . When the PV panel terminal starts to load, the PV panel voltage decreases and the PV panel current increases. While the current continues to rise after a point, the voltage decreases rapidly. When the PV panel reaches V_m and I_m values, maximum power is obtained from the PV panel.

Serial and parallel connection of PV panels In the PV panels connected to the series, the current of each passing through the system is equal. The system voltage for any current value is the sum of all PV panel voltages. The current of the PV system with serial connection is a single PV panel short-circuit current, and the voltage is a single PV panel open-circuit voltage. The total voltage of the circuit decreases considerably when there is shading in the series

of connected PV panels. Fig. 1.2.6. shows the I–V graph of the PV panels connected in series.

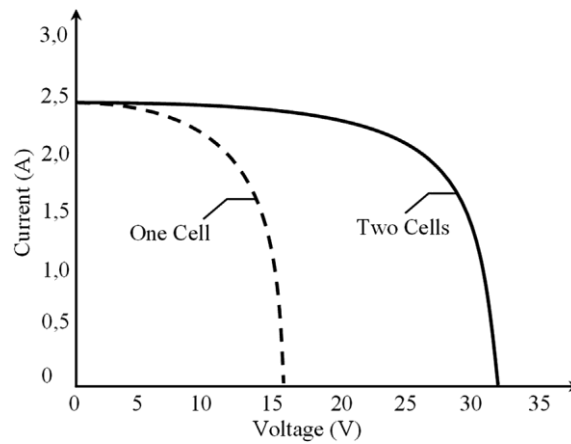


Fig. 1.2.5. I–V graph of series connected PV panels.

In a parallel connected system, a single PV panel voltage is the total voltage of the system. The current of each PV panels constitutes the total PV panel current of the system. The open-circuit voltage of the system is a single PV panel open-circuit voltage. The short-circuit current is the sum of the short-circuit currents of each PV panel. The partial shading in the parallel connected PV panel system does not change the total voltage in the system. But the total current value in the PV panel system is reduced. Fig. 1.3.1 shows the I–V graph of the parallel connected PV panels.

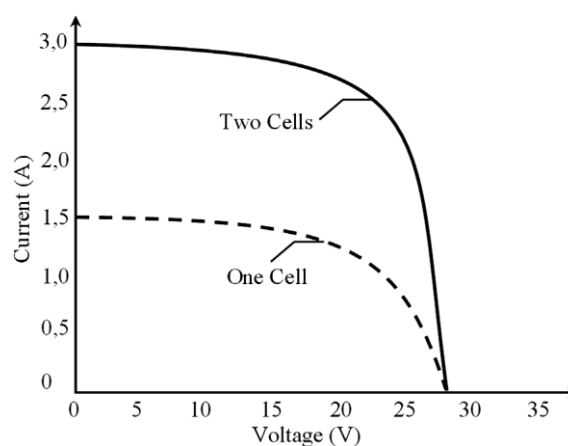


Fig. 1.2.6 I–V graph of parallel connected PV panels.

1.3. Solar cell electrical model

Single-exponent equation model is commonly used for the I–V characteristic of a solar cell and the power definitions that can be removed from this curve. The equivalent circuit of this model is given in Fig. 1.3.1 The equivalent circuit acts as a source of current depending on radiation. The relationship of current that can be obtained from a solar cell is given by the following equation:

$$I_{PV} = I_{ph} - I_d - I_p - I_o \left[e^{\left(\frac{qV_d}{KFT_{PV}} \right) - 1} \right] - \frac{V_d}{R_p} \quad (1.3.1)$$

where I_{ph} is current or short-circuit current produced by photons (A), I_o is re-verse leakage current (A), I_d is diode current in junction area (A), I_p is current through parallel resistor (A), R_p is parallel resistor (Ω), R_s is serial resistor (Ω),

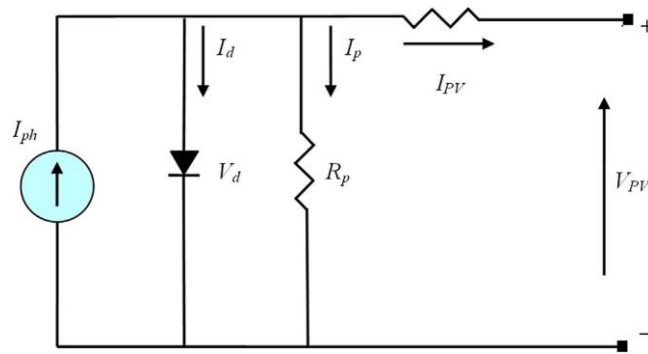


Fig. 1.3.1 Solar cell electrical equivalent circuit.

q is electron charge ($1.6 \cdot 10^{-19}$ C), K is the Boltzmann constant ($1.38 \cdot 10^{-23}$ J/K), T_{PV} is the absolute temperature of the solar cell (K), F is the ideal factor of the solar cell, I_{PV} is solar cell panel current (A), V_d is diode voltage (V), and V_{PV} is solar cell panel output voltage (V).

I_{ph} , the current produced by photons, varies depending on the radiation falling on the solar cell and the solar cell temperature as in the following equation:

$$I_{ph} = [\mu_{sc}(T_c - T_r) + I_{sc}]S \quad (1.3.2)$$

Where μ_{sc} is the temperature coefficient in the short circuit current of the solar cell, T_r is the reference temperature of solar cell, I_{sc} is short-circuit current at 1 kW/m^2 and 25°C , S is solar radiation in W/m^2 .

To determine the I–V curve with a single-diode model, the specific I_o and F parameters of the respective solar cell must be known. These parameters are usually not available in the manufacturer’s catalogs. The leakage current I_o can be measured with precise measurement possibilities. Also, according to the changing temperatures, the new values of I_o should be considered in the analysis. I_o changes exponentially with temperature. I_o saturation current is given in the following equation:

$$I_o = I_{oa} \left[\frac{T_{PV}}{T_r} \right]^3 e \left[\frac{qV_g}{KF} \left(\frac{1}{T_r} - \frac{1}{T_c} \right) \right] \quad (1.3.3)$$

$$I_{oa} = \frac{I_{sc}}{\left(\frac{qV_{PV}}{KFT_c} \right)} \quad (1.3.4)$$

where I_{oa} is the reverse saturation current of the solar cell at 1000 W/m² solar radiation and reference temperature (A), V_g is semiconductor bandgap voltage used by the solar cell (V), V_{OC} is the open-circuit voltage of solar cell (V), and F is the ideal factor of the solar cell. It depends on the solar cell technology used. Shows the values of the F factor according to the solar cell technology used.

Table 1.3.1

Ideal factor (F) values depending on solar cell technology

Solar cell technology	Ideal factor (n)
Si-poly	1.3
Si-mono	1.2
a-Si-triple	5.0
a-Si:tandem	3.3
a-Si:H	1.8

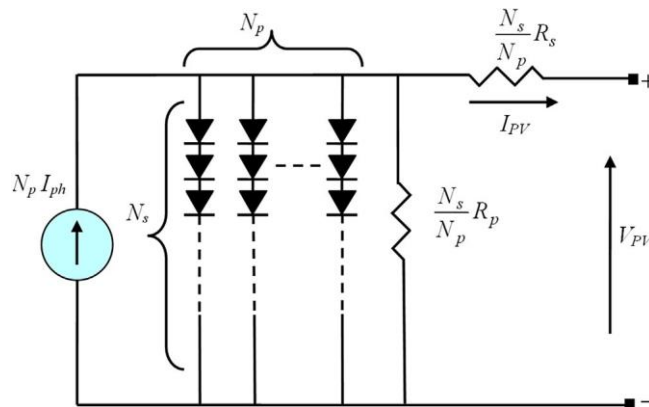


Fig. 1.3.2. PV panel arrays electrical equivalent circuit.

A solar cell is usually produced as 0.5 V 2 W. In order to increase this power, the solar cells can be connected in series or parallel to produce solar panels at desired voltage and current values. Fig. 1.3.2 shows the PV panel arrays circuit connected with the N_s series and N_p parallel.

According to the single-diode model, the total system consists of up to N_s series and up to N_p parallel connected solar cells. The I–V relation of the PV panel arrays is given in the following equation:

$$I_{PV} = N_p I_{ph} - I_o \left[e^{\left(\frac{q \left(\frac{V_d}{R_s} + I R_s / R_p \right)}{N_s K F T_{PV}} \right)} - 1 \right] - \frac{N_p V_d / N_s}{R_p} \quad (1.3.5)$$

Where N_s is the number of solar cells connected in serial, and N_p is the number of solar cells connected in parallel. In fact, the efficiency of the PV panel module R_s affects very little, while R_p has a greater effect.

A direct calculation of current and voltage values at the maximum power point of a PV panel is quite difficult due to the nonlinear I–V curve. Even if the internal resistance of the solar cell is neglected, the maximum power (P_m) from the PV panel is smaller than the $V_{si} \times I_{qt}$ value due to its electrical characteristic.

There is a need for rigid insertion to bring the term P_m closer to the $V_{si} \times I_{qt}$.

The maximum utilization rate of the I–V curve of a PV panel is defined by the fill factor (FF). The FF is expressed by the following equation:

$$FF = \frac{V_m I_m}{V_{si} I_{qt}} \quad (1.3.6)$$

The efficiency of a PV panel is the ratio of the electric power output (P_{out}) to the solar input (P_{in}). P_{out} is the output power of PV panel which can be accepted as P_{max} . A PV panel can be operated up to maximum power output. PV panel efficiency is given in the following equation:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{max}}{P_{in}} \quad (1.3.7)$$

1.4. Linear and tower concentrating solar power technologies

Thermal solar technologies can be divided into three applications: low-, medium-and high temperature. The most common example of low-

temperature applications is linear collector systems (LCS). Medium-temperature applications are LCS (PTCs, LFCs) and are given in Fig. 1.3.3. High-temperature applications include point concentrator systems [PDC and solar tower plants (STPs) with central receiver] and are given in Fig. 1.3.4.

Classic plate type linear solar collectors are mostly used in domestic hot water heating. Solar energy is transferred from heat to fluid by focusing. The temperature of the circulating fluid in these systems can reach up to 70°C–80°C.

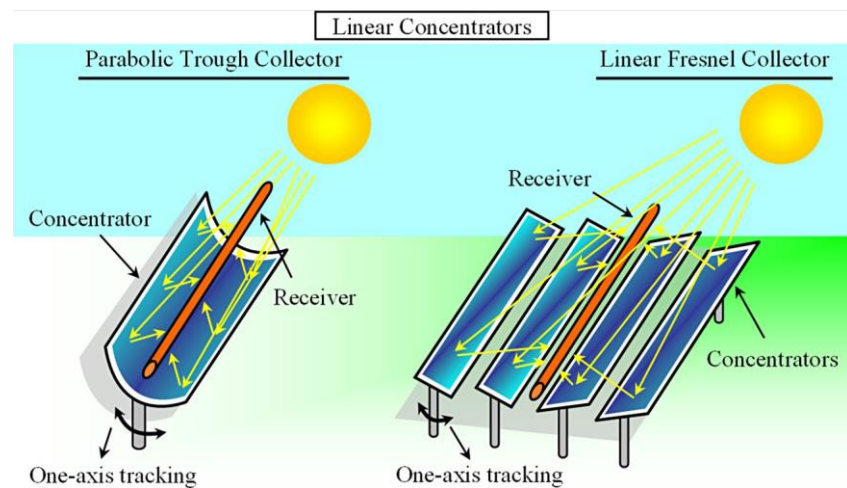


Fig. 1.3.3. Parabolic trough and linear Fresnel collector topology.

Apart from need for hot water, they are also used for hot water supply in swimming pools and small industrial facilities. In the last period the use of vacuum heat pipes has started to become widespread. The fluid temperature can reach up to 120 °C in the linear collectors.

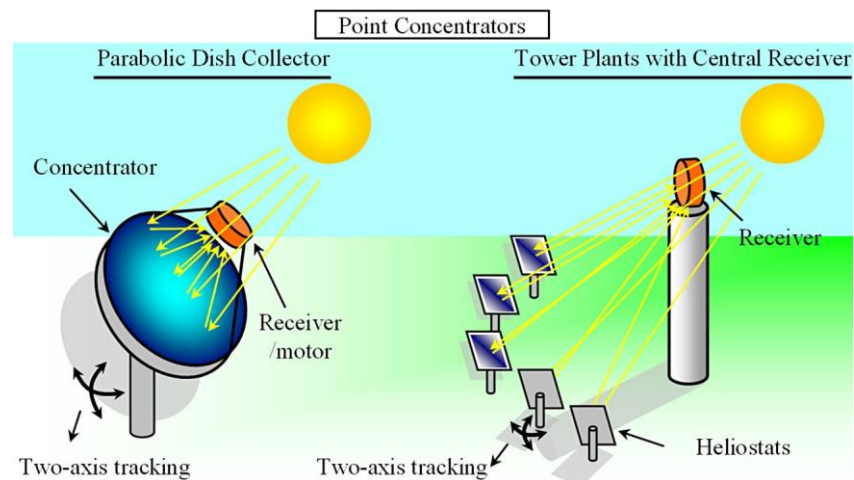


Fig. 1.3.4. Parabolic dish collector and tower plants topology.

The most common of thermal solar energy applications is water heating systems. Hot water preparation systems with solar energy vary depending on the way the water is used, the way the water is heated, and the circulation of the water in the system.

The second largest group of thermal solar energy applications is the parabolic and Fresnel trough collector systems. The temperature rises to 300 °C – 400 °C in these collectors. In tower plants with central receiver and dish collectors, the temperature can reach up to 1400 °C. Concentrators are intended to use direct sunlight at the highest possible rate. For this purpose the sun collectors are equipped with a monitoring mechanism that allows the sun to be continuously monitored.

Parabolic trough collector power system (PChK) are composed of parabolic arrays that can make linear condensation. Reflective surfaces on the inside of the trough reflect sunlight to a black absorbent pipe located at the focus of the parabolic. The heat-collecting glass tube consists of steel receiver pipes and glass-metal connectors with an absorptivity of approximately 97 % on the surface. The air between the glass tube and the receiving pipe is vacuumed to reduce heat losses due to high temperature occurring on the receiving pipe. This gap pressure is about 0.1 atm.

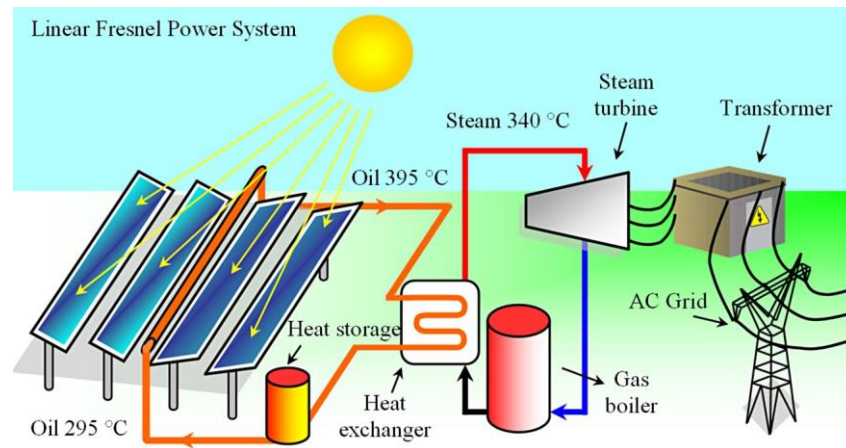


Fig. 1.4.1. Parabolic trough power system diagram.

The heat-resistant glass tube has a high permeability and an antireflective structure to minimize radiation losses. Glazed glass-metal binders are used to remove the effects of temperature expansions. The system has an automation-tracking control unit that allows the mirrors to monitor the sun.

Solar energy collectors can obtain saturated or superheated steam at medium and high temperatures. Industrial plants can be used directly for thermal purposes; it can also be used in electricity production by passing through a suitable thermodynamic cycle. The general operation principle of parabolic trough power system is shown in Fig. 1.4.1. In the first phase of such plants, the heat transfer fluid circulates. This fluid is usually high-temperature synthetic oil. By means of a synthetic oil heat exchanger, the water contained in the electrical power generation system is converted into a steam phase. This superheated steam is generated electricity through the turbine generator. There is a heat storage unit in the cycle to ensure the continuity of electricity generation. In this heat storage unit, the salt melt is generally used. When the sunlights are insufficient, the heat storage unit is activated and plays a supporting role in the evaporation of water in the power circuit.

In thermal solar power plants, one of the most important measures implemented in recent years for continuous and regular electricity production is the use of hybrid systems. The use of hybrid energy sources plays an important role in ensuring the uninterrupted operation of plants.

Steam generation system consists of preheating, steam generation, and superheating sections. Steam is passed through these sections to 400 °C and 100 bar pressure. It is sent to the turbine for electricity generation. After the electricity generation, the steam that is not cooled sufficiently is heated to the same temperature and sent back to the turbine without being sent to a new cycle. In this second cycle the residual cooling steam is sent to a new cycle after it becomes liquid. These systems, which can produce 25–200 MW of electricity in terms of the highest radiation, are generally the lowest cost electric power plants per kW h.

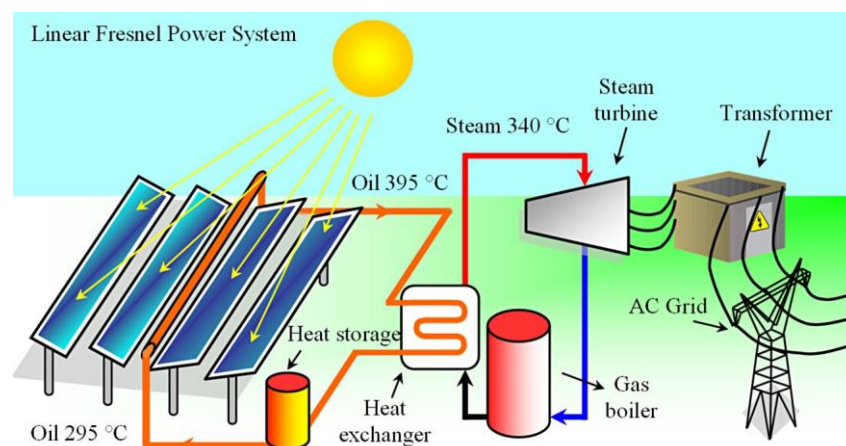


Fig. 1.4.5. Linear Fresnel power system diagram.

Linear Fresnel power system High temperatures can be achieved with linear or point concentrators in CSP technologies. Linear Fresnel power (LFP) plants are constructed using one-dimensional planar mirrors. A heat-collecting tube is placed along the focal point of the mirrors. In linear concentrator systems, the sunlight is collected on a linear focus by the reflective surface. The fluid passing through the pipe forming the surface is heated. The focus mentioned here as a line is a narrow and long space in the form of strips. The temperature of the fluid varies depending on the flow rate, concentration ratio, and the instantaneous solar radiation value. The highest theoretical temperature in linear concentrator systems is very close to the temperature of the sun. The control unit is available for the linear mirrors to follow the sun. An LFP system diagram is shown in Fig. 1.4.2.

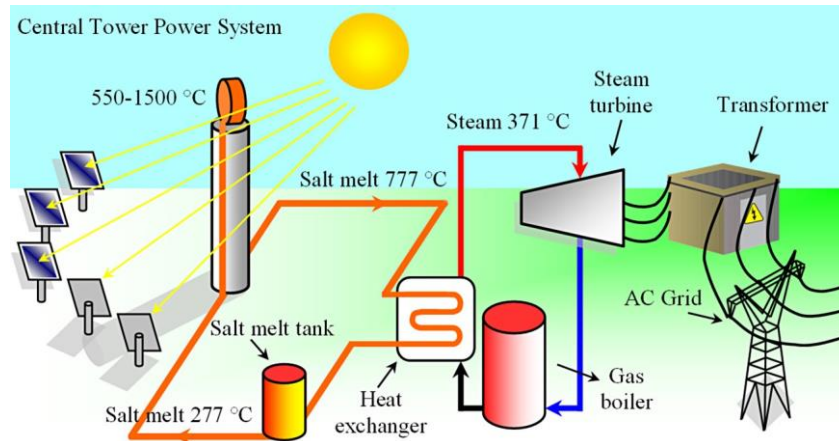
Point concentrator systems (PCS)

Parabolic dish collector power system Dish collector systems consist of dish, collector, and a motor unit. The solar energy is densified to a receiving surface by a dish-shaped surface. A Stirling or a Brayton engine is used as receiving surface. The receiver may be used as the direct heat energy of the radiation collected on the surface or transfer to the fluid in a Stirling engine. The Stirling engine converts heat into mechanical power. A gas of low specific gravity such as hydrogen or helium is preferred in these systems. The compressed gas expands by being heated by the sunlight.

The cylinder pistons in the Stirling engine move with this gas. This mechanical power is converted into electrical power by means of a generator. Dish systems follow the sun in two axes. It is very suitable for droughty environments where water sources are not available since the water cycle is not used in the collector systems. As it is modular, it can be used as a single or as many dishes. However, it is difficult to make a stable and economical Stirling engine. Hydrogen and helium gases, which are lightweight, should not leak for the robust operation of Stirling engines. In addition, it is not possible to store energy in dish collector systems. Therefore, it is recommended that the dish collector systems be designed in conjunction with another energy source in a hybrid structure.

Central tower power system Central tower power systems consist of hundreds of heliostat mirrors spread over a wide area. Heliostats concentrate the

sunlight on the tower to the collector by performing two-axis solar tracking. A central tower power system diagram is given in Fig. 1.16. The temperature of the salt melt circulated through the collector increases with the help of this concentrated radiation. The salt melt efficiently absorbs heat and is pumped from the storage tank at 277 °C into a collector on the tower. The salt melt is heated to 777 °C in a tower and stored in a salt melt tank. When the power is



needed, the salt melt is pumped into a boiler and used to produce superheated steam. In solar tower systems, the condensing rate varies between 300 And 1500, while the temperature can range from 550 °C to 1500 °C. The maximum electrical power is 10 MW in central tower power plants. It is the most efficient among the concentrating solar power (CSP) systems. As the operating temperature in heliostat systems is very high compared to the others, reliability and robustness are the most important factors.

Fig. 1.4.3. Central tower power system diagram.

The heliostats are controlled by a computer to ensure that the tower collector is continuously receiving sunlight. As STP systems require complex structure and high technology, investment costs are high.

1.5. Advantages and disadvantages of solar systems

Renewable energy sources (RESs) are being replaced by fossil fuels to produce electricity in today's and future technologies. Solar energy is clearly more environment friendly compared to all other energy sources, so its use is increasing worldwide. RESs are inexhaustible and no harmful gases such as

CO₂ leave solid wastes.

The following are the advantages of RES:

- the amount of greenhouse gases released into the environment is zero (CO₂, NO_x),
- no release of toxic gases to the environment throughout using of sources (SO₂, particles),
- making barren lands useful,
- decreasing the transmission line costs in existing electricity grids,
- allow for individual installation and use,
- provide national energy independence to countries, and
- the rapid increase in the rate of use in rural areas.

The use of solar energy is encouraged to meet the rapidly increasing energy consumption demand, to prevent global climate change and to minimize greenhouse gas emissions. International regulations are launching to ensure easy access to these resources. Countries add the issue of generating electricity from RES to their national strategic objectives. Countries are trying to establish various solar energy policies within this framework. Moreover, different areas of the world are being worked for the use of solar energy in electricity generation. Advantages and disadvantages of PV panels are given in Table 1.4.1. Advantages and disadvantages of CSP systems are given in Tables 1.4.2. and 1.4.3. When the CSP systems are examined in terms of technological, economic, and area utilization and ease of operation, the differences between these systems are as follows:

Technologically

PTC: Their efficiency is low because they make solar tracking on one-axis and linear condensation. The solar tracking unit of these systems is cheap and simple. These systems can be used in low and high electrical power plant applications. The manufacture of heat-collecting pipes and mirrors used in the system requires special technologies.

LFC: Their efficiency is low because they make solar tracking on oneaxis and linear condensation. The solar tracking system is cheap and very simple. It can be used in all applications with low and high power when it is used as an electrical power plant. There are no elements that require special technology.

Table 1.4.1.

Advantages and disadvantages of PV panels

PV panels	
Advantages	<ul style="list-style-type: none"> • PV panels do not release harmful greenhouse gas emissions during electricity generation • PV panels can be made available wherever there is sunlight • PV panels are suitable for smart grid structures with distributed power generation • PV panel costs are on the way to a rapid decline thanks to developing technology • Direct electrical energy can be achieved with PV panels • The operating and maintenance costs of PV panels are almost negligible compared to other RES • PV panels do not produce any sound during operation. Suitable for urban areas and residential applications • PV panel installations are quite easy and do not require special equipment • There are incentives for PV panels to increase use in many countries • Thanks to the financial incentives provided to PV panels, an attractive investment is becoming an alternative
Disadvantages	<ul style="list-style-type: none"> • As with all RESs, electrical energy generated from PV panels depends on the natural events • The electrical energy generated from PV panels is intermittent and unstable. It requires an energy storage unit to eliminate this disadvantage • The use of the energy storage unit together with the PV panels increases the cost • PV panels produce direct current (DC) electrical energy. An inverter is required for use in the alternative current (AC) electricity grid • Large powerful PV panel systems require large area for installation • PV panel efficiency levels are relatively low in today's technology (14 %–25 %) • The surfaces of PV panels must be cleaned periodically in order not to reduce system efficiency

DC: The solar tracking system is of two axes. A special motor (Stirling or Brayton engine, etc.) may be required in the focusing unit. It requires special engineering.

STP: Their efficiency is high because they make solar tracking on two-axis

and point condensation. Solar tracking systems are expensive and complex. Low power and small sizes cannot be produced. The support structure carrying the heliostats is large and bulky.

Economically

PTC: Costs are high due to the special technology of heat-collecting pipes and mirrors. It can be used to generate electricity or to produce heat at medium-high temperature.

Table 1.4.2.

Advantages and disadvantages of PTC and LFC

	Linear concentrators	
	Parabolic trough collector	Linear Fresnel collector
Advantages	<ul style="list-style-type: none"> • Operating potential up to 600 °C • About 14 % net electricity production efficiency annual • Applicable investment and operating costs • Modular structure • Good land use factor • Minimum material demand • Hybrid concept applicable • Thermal storage capability 	<ul style="list-style-type: none"> • Easy setup • Lower installation costs compared to other solar systems • Reflective flat mirrors are sufficient • Low production costs • Hybrid processing possible • 1.5–3 Times more energy per land area is produced • The most land-efficient solar energy technology
Disadvantages	<ul style="list-style-type: none"> • Oil-based heat transfer is used during heat cycle. It limits operating temperatures to 400 °C in oil-based system. Therefore the steam quality produced is moderate 	<ul style="list-style-type: none"> • Low system efficiency due to low operating temperature • Implementation only in low power plants

Table 1.4.3

Advantages and disadvantages of DC and STP.

	Point concentrators	
	Dish collector	Tower plants with central receiver

Advantages	<ul style="list-style-type: none"> • Small land requirement than other solar systems • High working temperature • High thermodynamic efficiency • High sunlight collecting rate thanks to two-axis solar tracking 	<ul style="list-style-type: none"> • High conversion efficiency in terms of system • Operating temperature potential above 1000 °C • Thermal storage at high temperatures • Hybrid concept applicable • Suitable for dry cooling concepts • Good for use in rough areas
Disadvantages	<ul style="list-style-type: none"> • Low thermal storage capability • High engineering requirements • High installation cost 	<ul style="list-style-type: none"> • Large land requirement • Higher installation costs than other solar systems • Complex control mechanism

LFC: There is no special part requiring technology. Due to its simple structure, unit cost is the lowest among all systems. It can be used to generate electricity or to produce heat at medium-high temperature.

DC: Costs are high because it requires the use of special motors in the heat collection unit. These systems use a lightweight gas as a heat exchanger and, therefore, require a special installation infrastructure.

STP: It is an expensive system due to the bulky structure of towers and heliostats used for sunlight collection. It is suitable for electrical energy production purposes.

In terms of area utilization and ease of operation

PTC: In order for the mirrors to not shade each other, it is necessary to leave a certain amount of space between the mirror arrays. At least three times the active mirror area is required. The two most important elements of the system are heat-collecting pipes and special technologies mirrors. In the case of failure, original spare part supply and sometimes outsourced workmanship is required. Cleaning of mirrors or reflective surfaces is important for system efficiency. In addition, vacuum must be provided in the heat-collecting pipe.

LFC: A mirror settlement area of 1.1–1.2 times of the active mirror area is sufficient. The whole system can be produced with local materials and workmanship. Because of its simple structure, all maintenance and repairs can be carried out with the standard maintenance team.

DC: There is not much space for mirrors. In order to prevent the leakage of the gas used as a heat exchanger in the system, their maintenance should be done

frequently. Due to the special motor, there may be outsourced workmanship and material requirements.

STP: A mirror settlement area of approximately 10 times the active mirror area is needed. It is possible to use a large proportion of local materials and workmanship. It is therefore relatively easy to operate and repair.

CONTROL QUESTIONS:

1. How is solar energy produced?
2. How are wind and ocean waves formed?
3. What technologies are used for direct collection of solar energy?
4. What type of diodes are used to convert sunlight directly into electrical energy?
5. What type of diodes are used to convert sunlight directly into electrical energy?
6. Explain the distribution of solar radiation.
7. What materials are used to manufacture solar panels?
8. Which semiconductor elements are most commonly used in solar panel production?
9. How does a photovoltaic power station operate step by step?
10. How does the I–V characteristic (Volt–Ampere Characteristic) change when panels are connected in series and parallel?
11. How does a central tower solar power system operate?
12. What are the advantages and disadvantages of PV (Photovoltaic) and CSP (Concentrated Solar Power) technologies?
13. What are the advantages and disadvantages of photovoltaic panels?

Chapter II

ELIMINATE THE DISADVANTAGES OF, RENEWABLE ENERGY SOURCES

2.1. Disadvantages of renewable energy sources

Although renewable energy sources (RES) come from nature, there are processes in which the energy they produce is interrupted. RES are affected by natural events such as sun, wind, wave, and tide. Wind energy can only generate energy in times when the wind blows. In the same way, offshore energy sources can provide energy when there are waves, currents, and tides. Solar energy systems produce energy depending on hourly, daily, and seasonal conditions.

In photovoltaic (PV) panels the shading effect occurs when a PV array or part of it is not fully irradiated. When PV panels have partial shading, the PV panel acts as if there is a load in the system instead of generating energy. If this reverse tendency exceeds the degradation voltage of the shaded PV cell, it may function as an open circuit and damage the entire PV module. To reduce the effects of PV panel partial shading, PV panel manufacturers add bypass diodes to the modules. However, the number of diodes in the PV panel is less than the number of cells connected in series within the module. As a result, the PV panel open-circuit case is reduced. However, the total power output is reduced as the PV panel remains unstable. Fig. 2.1 shows two series of PV panels in partial shading state.

There is a bypass diode connected in parallel to the PV panel array in PV arrays at the first row. There is no partial shading in these PV panels. PV arrays in the second row have partial shading. The power produced by the PV panels in this sequence is lower.

Fig. 2.2 shows the V–P curve of the PV module in fully irradiation and partial shading conditions. In the case of partial shading of PV panels, two different power points emerge. One of these points is the actual maximum power point (MPP) and the other is only the peak power point. The peak power point is due to the bypass diode in the PV modules. MPP algorithms need to work correctly to find the actual MPP in such cases.

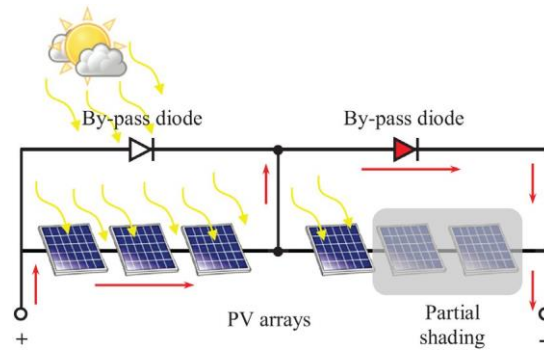


Fig. 2.1.1. Power flows of PV arrays in the case of partial shading.

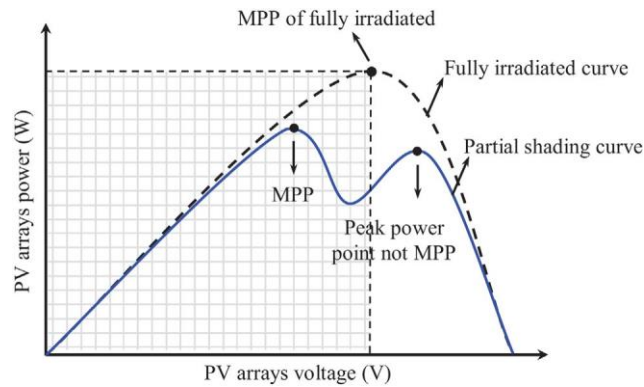


Fig. 2.1.2. MPP changes of PV arrays under partial shading.

PV power generation systems have two major problems in terms of efficiency and low irradiation. The efficiency of these power conversion systems is very low (9 %–17 %). Particularly, under low irradiation conditions, the amount of electrical energy produced by the solar panels changes constantly depending on the weather conditions. Moreover, the electrical characteristics of the solar panels draw a nonlinear curve with varying temperature and radiation. This peak, which is often displaced continuously on the I–V or V–P curve, is called the MPP. Maximum power point tracking (MPPT) control technique is a method that enables efficient use of PV panels. This method is a control structure that captures the highest point of the solar panel. This power point varies with variables such as radiation, temperature, PV panel slope, and PV panel aging. When the entire PV system (arrays, converters, etc.) is operated at this power point, it operates at maximum efficiency and receives maximum output power from the PV panel.

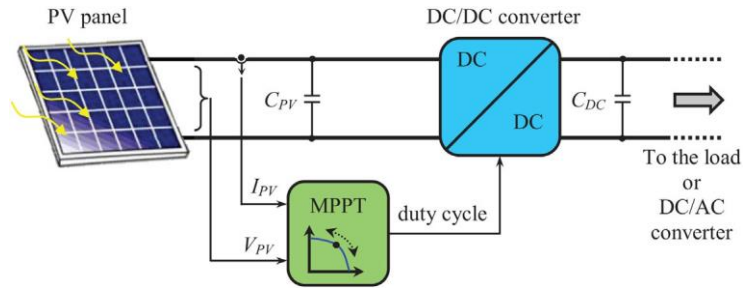


Fig. 2.1.3. Implementation of MPPT technique to the PV panel.

MPP can only be detected by computational models or by search algorithms. In order to perform this process, the control mechanism evaluates the PV panel variables depending on the control technique and changes the reference of the power converter to reach the power point. The more input units associated with the PV panel in the system, the closer and more stable the control system is to the MPP. However, too much input increases the number of operations in the run algorithm and may result in late response time. As a result, it may be delayed in capturing MPP in rapidly changing weather conditions, which is undesirable for the system. Therefore the use of a technique that provides the same operating efficiency with fast response time without forcing the processing algorithm with the minimum input unit becomes important in terms of cost and simplicity. Fig. 2.1.3. has shown the use of the PV panel in a system and the topology of the MPPT method.

2.2. Maximum power point tracking operating principle

The electrical characteristic of the solar cell in the case of specific irradiation is shown in Fig. 2.2.1. The internal resistance of the solar cell is high on the left side of the curve and low on the right side.

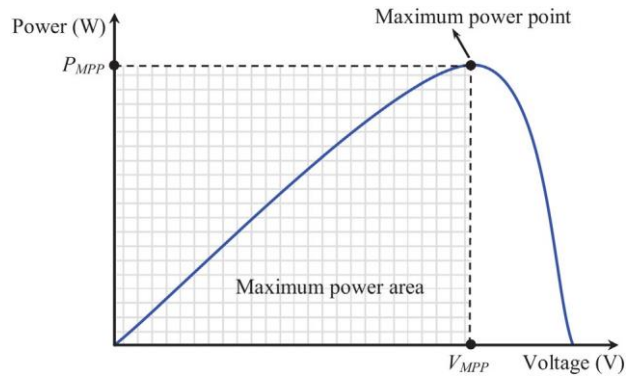


Fig. 2.2.4 Electrical characteristic of PV panel for a specific irradiation condition.

The MPP is at the exact peak of this curve. According to the maximum power transfer theory, the maximum power is transferred to the load when the source and load impedances are equal. When the impedance of the switched converter is equal to the impedance of the solar panel, the condition of operation at the MPP is provided. Many conventional DC/DC converter circuits have naturally negative impedance characteristics. This behavior is due to the constant input power character and the adjustable output voltage of the power supply. If the system is operated on the high impedance side (low-voltage side) of the solar module characteristic curve, the PV panel voltage will decrease. Therefore in the case of MPPT, the solar panel must be operated in the right zone of the characteristic. Otherwise, the PV panel voltage will change according to the irradiation condition, while the PV panel will operate in the maximum duty cycle rate. Thus the system will not reach MPPT and will operate at the wrong point. In electrical systems used as PV panel source, a nonlinear change in the output voltage occurs due to the structure of the PV panels. PV panel output voltage change is seen in Fig. 2.4. The output voltage of the PV panels differs depending on the current drawn, as well as the intensity of the sunlight falling on the PV panels and the ambient temperature. The mentioned output power of commercial PV panels is determined as the electrical energy that the PV panel can generate in an environment where the intensity of the irradiation per unit area is 1000 W/m^2 . It is assumed that said output power is the maximum power that the PV panel can deliver. As the intensity of the sunlight decreases, the current that can be drawn from the PV panel decreases is seen in the curve in Fig. 2.2.2 Fig. 2.2.2. shows that the PV panel current is 2.3 A and the voltage is 19 V in an environment with 1000 W/m^2 irradiation (A point). In this case the power

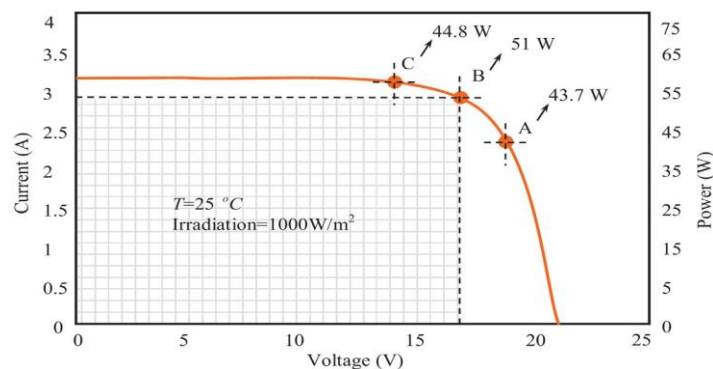


Fig. 2.2.5. Current–voltage and power–voltage curve of PV panel

Generated at point A is 43.7 W. When the current drawn from the PV panel is operated at 3 A in the same irradiation, the curve shows that the output voltage drops to 17 V (B point). The power produced according to the new current voltage values is 51 W. In the same case, 3 A is drawn from the PV panel at point C and the output voltage is 14 V. The power generated at point C is 44.8 W.

As a result of these values, although the load increases gradually, the amount of power that can be taken from the PV panel varies in a nonlinear manner. The power generated up to a point increases depending on the load but decreases at the power generated after a point. If this situation is not kept under control, the system will operate with low efficiency. MPPT systems always try to keep this output power at its peak. The MPPT circuits include a design infrastructure that is much more than a simple current limiter.

Under varying temperature and irradiation conditions, the MPP of the PV panel is constantly changing so the PV system must be changed to produce maximum power at the operating point. Therefore MPPT techniques are used to enable PV panels to work in MPP. There are many MPPT techniques to capture the MPP of PV panels. These commonly used techniques are constant voltage method, constant current method, short-circuit current pulse method, open voltage method, perturb and observe method, incremental conductance method, and temperature method.

Constant voltage method The constant voltage algorithm is a simple MPPT control method. This algorithm tries to keep the panel close to the MPP by matching the PV panel voltage and a constant V_{ref} reference voltage. This V_{ref} value is the characteristic V_{MPP} of the PV panel. This method assumes that the temperature variations of the only PV panels are insignificant and that the constant reference voltage is a sufficient approach to the actual MPP. Therefore the process can never be processed in the full MPP, and different data must be collected for different geographical areas. In the constant voltage method, it is necessary to measure the PV panel voltage of the solar panel in order to establish the duty cycle and to process the algorithm in the block diagram given in

Fig. 2.2.3. When low irradiation conditions of the PV panel are important, it is observed that the constant voltage technique is more effective than the perturb and observe method or incremental conductance method.

The constant voltage method is a simple, inexpensive, and convenient

method that does not require complex circuits. However, the need to separate the

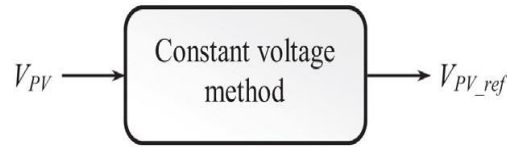


Fig. 2.2.6. Constant voltage method block diagram.

Load from the PV module in order to read the V_{PV} voltage information required to generate a reference mark is a problem for loads. The lack of utilization of solar energy during PV panel voltage measurement and the inability to sustain the actual MPPT process are negative effects.

Short current pulse method The short-circuit current pulse method manages to operate in the MPP by providing the current controlled power converter I_m operating current. In fact, the optimum operating current I_m for maximum output power is proportional to Eq. (2.1) with the irradiation level S under various conditions and the short-circuit current I_{ph} .

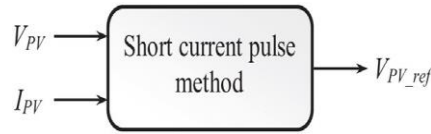
$$I_m(S) = k \cdot I_{ph}(S) \quad (2.2.1)$$

Where k is a proportional constant and I_m can be determined immediately when I_{ph} is detected in Eq. Although the temperature varies from 0°C to 60°C , this relationship between I_m and I_{ph} is continuously proportional. This proportional parameter is estimated to be about 92 %.

Therefore this control algorithm requires I_{ph} measurement. To achieve this measurement, a parallel static switch must be connected to the PV panel to generate a short-circuit current. In the case of a PV panel short circuit, no power is obtained from the PV panel and power generation is stopped. For the short current pulse algorithm, V_{PV} and I_{ph} data must be processed in the block diagram given in Fig. Although the short current pulse method is simple and does not require complex circuits, energy is lost during the measurement of the short-circuit current of PV panel. Due to the determination of the constant k and the contamination that may occur on the panel surface, deviations of the constant k are among the negative effects of this method.

Open voltage method The open voltage method is based on the observation that the voltage at the MPP is always close to the percentage of open-circuit voltage. The temperature and solar irradiation level change the position of the

MPP within the 2 % tolerance band. In general, the open voltage method uses 76 % of the open-circuit voltage of the panel as the optimum operating voltage, and maximum output power can be obtained from the PV panel. For



this control algorithm

Fig. 2.2.7. Short current pulse block diagram.

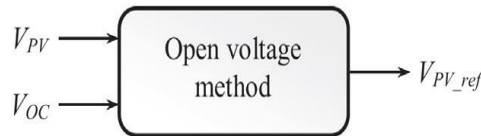


Fig. 2.2.8. Open voltage method block diagram.

The open-circuit voltage V_{OC} shown in the block diagram in Fig. 2.8 must be measured. This method uses a static switch with the PV panel and must be connected in series to the PV panel to open the switch circuit. When $I_{PV} = 0$, no power is generated by the PV system and as a result, the total energy from the PV panels is reduced.

Perturb and observe method The perturb and observe method is one of the most commonly used methods. This method changes the fluctuating (increasing or decreasing) PV panel voltage or current at intervals and operates by comparing the PV output power with the previous power value. If the PV panel operating voltage changes and the power rises, the control system PV operating point changes in this direction, otherwise the operating point moves in the opposite direction. In the next cycle the algorithm continues in the same way. In the perturb and observe method, the PV output power is continuously monitored and a correlation between the movement of the control variable and the movement of the power is determined to reduce or increase the reference. It has weaknesses such as slow response to rapid change of atmospheric conditions. and searching the MPP in the wrong direction for sudden changes. Since the system continuously making perturb and observe, it is not fixed here when it reaches MPP. It continuously oscillates around the MPP and there is some power loss in the system.

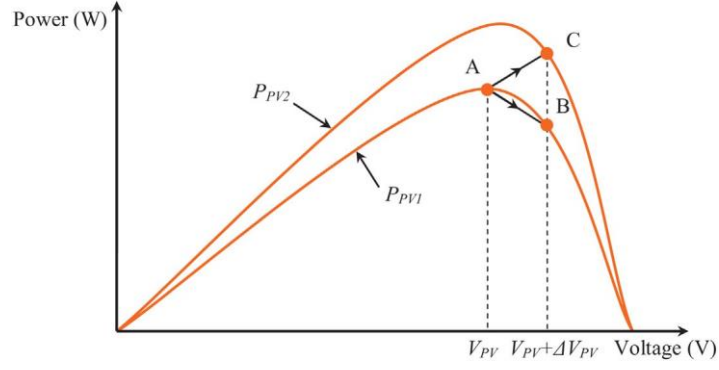


FIG. 2.2.9. The change of maximum power points in the perturb and observe method.

While the power decreases in the left region of the MPP, the PV panel voltage also decreases as shown in Fig. 2.2.9. In the right region of the MPP, the power decreases as the PV panel voltage increases. Therefore if there is an increase in power, the next perturb should be kept the same to reach the MPP, and if there is a decrease in power perturb must be reversed. Perturb and observe algorithm can also be applied on the basis of voltage to power or current to power variation. As a result of the comparison process, the next pulse width ratio is determined to achieve the MPP. Perturb and observe method, as seen in Fig. 2.2.9, can work incorrectly in rapidly changing atmospheric conditions. When starting at point A, when the atmospheric conditions remain approximately constant, perturb of the PV panel voltage ΔV will move the operating point to B and the next perturb will be reversed due to a reduction in power. However, if solar irradiation increases, the power curve shifts from P_{PV1} to P_{PV2} within a sampling time, and the operating point is moved from A to C. This means an increase in power and perturb is kept the same. Therefore the operating point is separated from the MPP and if the solar irradiation increases continuously, the operating point remains separated from the MPP. The actual power point is compared with the two previous points before a perturb signal decision is made to ensure that the MPP is monitored even in the case of momentary changing solar irradiation.

The flow diagram of the perturb and observe algorithm is given in Fig. 2.2.10. In this algorithm, first the current and voltage values from the sensors are read, and the power of the PV panel is calculated. This power value is compared with the previous value. If there is an increase or decrease in power, the voltage of the PV panel is compared with the previous voltage value as in

power. If there is a decrease in power and an increase in voltage value, it is determined that the MPP is perturb in the right region. To capture the MPP the reference voltage must be reduced. However, if there is a decrease both in power and voltage, it is determined that the MPP is perturb in the left region, and the reference voltage must be increase. This process continues until the MPP is reached and then the algorithm circulates around the MPP. If this sampling step is large, the system will oscillate at points remote from the MPP, reducing the total amount of energy from the PV panels. However, a smaller perturb slows the MPPT and causes late response time. As a solution, MPP should be approached using small perturbs. In order to calculate the power, it is necessary to measure the voltage and current of the PV panel given in the block diagram in Fig. 2.11.

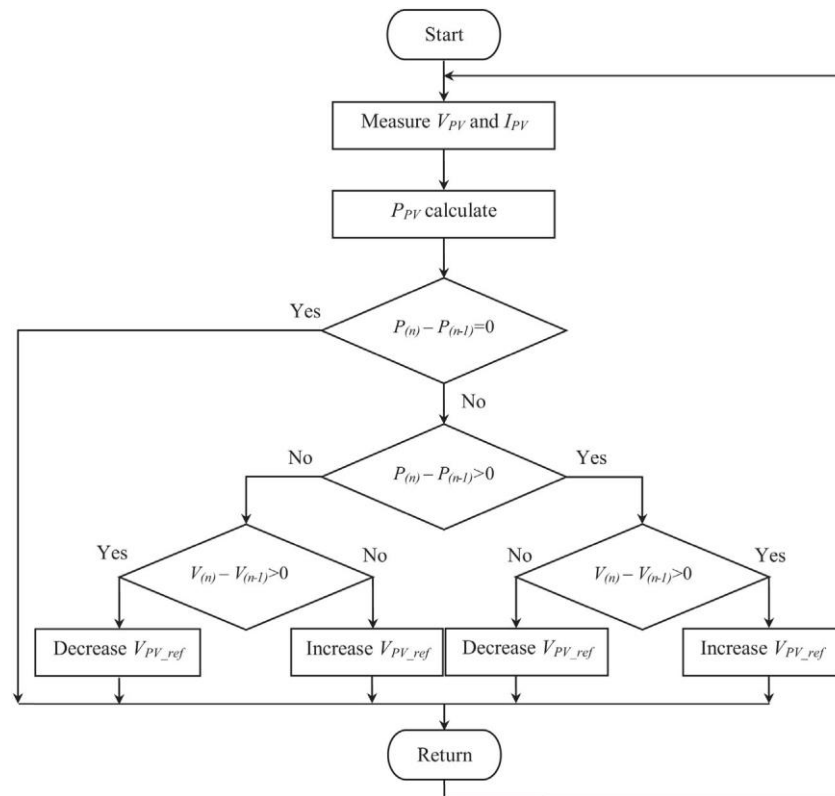


FIG. 2.2.10. Flow diagram of perturb and observe method.

Incremental conductance method. This incremental conductance algorithm is based on the logic of finding the MPP with the conductivity of the PV panel. It has been proposed to quickly detect changes in atmospheric conditions. The incremental conductance algorithm is based on the principle of following the MPP by comparing the incremental and instantaneous

conductivity of the PV panel. Sample changes in the current and voltage values produced by the PV panel may also change the conductivity gradually increasing. This method is based on Eq. (2.2). This is to see the change in pv panel power due to the voltage and set the result to zero. V–P characteristic curve showing the dP_{PV}/dV_{PV} change of the PV panel is given in Fig. 2.2.11.

$$\frac{dP_{PV}}{dV_{PV}} = I_{PV} \frac{dV_{PV}}{dV_{PV}} + V_{PV} \frac{dI_{PV}}{dV_{PV}} = I_{PV} + V_{PV} \frac{dI_{PV}}{dV_{PV}} = 0 \quad (2.2.2)$$

$$-\frac{I_{PV}}{V_{PV}} = \frac{dI_{PV}}{dV_{PV}} \quad (2.2.3)$$

The left side of Eq. (2.2.3) expresses the contrast of incremental conductance. The right side of Eq. (2.2.3) shows gradually incremental conductance and can be written as shown in the following equation:

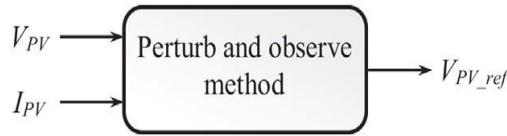


Fig. 2.2.11. Perturb and observe method block diagram.

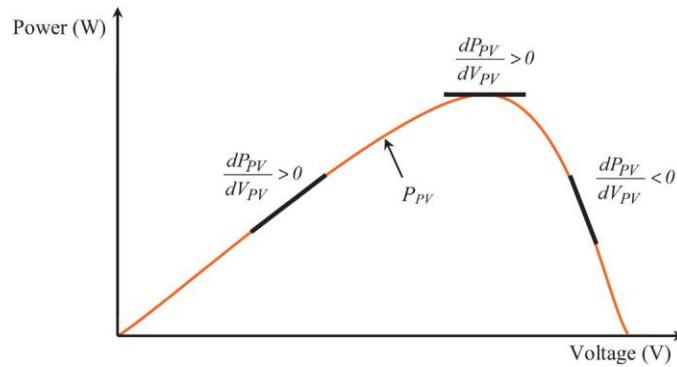


Fig.2.2.12. V–P characteristic curve showing the dP_{PV}/dV_{PV} change of the PV panel.

On the other hand, the incremental variables dV_{PV} and dI_{PV} are both obtained by comparing the instantaneous measurements with the previous instantaneous measurements, which are given in the following equations:

$$G = \frac{dP_{pv}}{dV_{pv}} \quad (2.2.4)$$

$$dV_{pv}(n) = V_{pv}(n) - V_{pv}(n - 1) \quad (2.2.5)$$

$$dI_{pv}(n) = I_{pv}(n) - I_{pv}(n - 1) \quad (2.2.6)$$

Thus by analyzing the derivative of the P_{PV} , it can be tested that the P_{PV}

operates at or beyond the MPP. In Eq. (2.7) the operating is to the left of the MPP and the V_{PV} panel voltage is less than the voltage in the V_m MPP. The V_{PV} is equal to the operating in the V_m MPP and is given in Eq. (2.2.8). The V_{PV} panel voltage is more than the voltage in the V_m MPP and is given in Eq. (2.2.9). It is seen that the study is to the right of the MPP and the V_{PV} panel voltage is greater than the voltage at V_m MPP.

$$\frac{dP_{PV}}{dV_{PV}} > 0 \quad \text{uchun } V_{PV} < V_m \quad (2.2.7)$$

$$\frac{dP_{PV}}{dV_{PV}} = 0 \quad \text{uchun } V_{PV} = V_m \quad (2.2.8)$$

$$\frac{dP_{PV}}{dV_{PV}} < 0 \quad \text{uchun } V_{PV} > V_m \quad (2.2.9)$$

According to Eq. (2.2), the instantaneous conductivity ($\frac{dI_{PV}}{dV_{PV}}$) and incremental conductance ($\frac{\Delta I_{PV}}{\Delta V_{PV}}$) can be compared to the MPP point as shown in the flow diagram in Fig. 2.13. At the MPP point the reference voltage V_{ref} is equal to the V_m voltage in MPP. When the MPP is reached, the PV panel operating point is maintained at this point, if no change is observed in the MPP or a change in atmospheric conditions. The algorithm increases or decreases the V_{ref} reference voltage to monitor the new MPP. In order to calculate the power in this control algorithm, it is necessary to measure the PV panel voltage and current shown in the block diagram in Fig. 2.14.

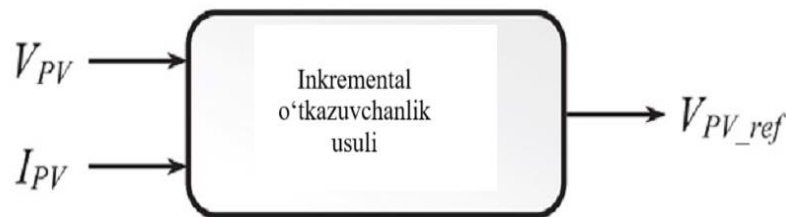


Fig. 2.13. Flow diagram of incremental conductance method.

The most important advantage of the incremental conductance method is that it can adapt to rapidly changing atmospheric conditions and that the oscillation in the MPP is much less than that of the perturb and observe method. However, circuits controlled by the incremental conductance control method are somewhat more complex and expensive.

Temperature method. The open-circuit voltage often varies with the V_{oc} PV cell temperature but does not change in a relatively direct proportion on short-circuit current, irradiation

level, and PV cell temperature changes. The following equation defines the open-circuit voltage V_{OC} of PV cell:

$$V_{OC} \cong V_{OCSTC} + \frac{dV_{OC}}{dT_{PV}} \cdot (T_{PV} - T_{STCPV}) \quad (2.10)$$

Where V_{OCSTC} is the PV cell open-circuit voltage under the standard test conditions (STC), T_{STCPV} is the PV cell temperature under STC. On the other hand, the MPP voltage V_m in each operating condition is expressed by the following equation:

$$V_m \cong [(u + S \cdot v) - T_{PV} \cdot (w + S \cdot y)] \cdot V_{m-STC} \quad (2.11)$$

Where V_m STC is the MPP voltage under STC. Table 2.1 shows the parameters of the optimum voltage equation with respect to the S irradiation level.

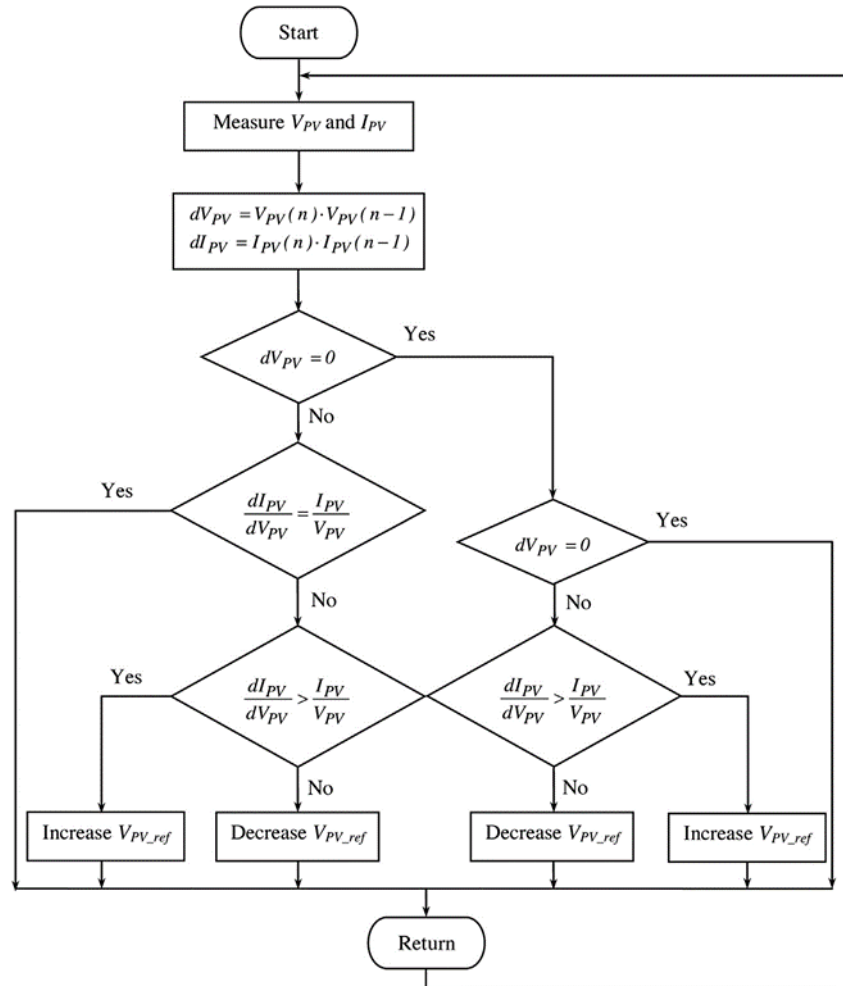


Fig. 2.14. Incremental conductance method block diagram

The temperature parametric equation method calculates according to Eq. (2.11) and determines the MPP voltage by measuring the T_{PV} and S values.

The temperature parametric method generally also requires S solar irradiation. Fig. 2.15 shows the block diagram of the temperature method.



Fig. 2.15 Temperature method block diagram.

2.3. Compare of MPPT techniques

MPPT techniques vary in many aspects, including simplicity, convergence speed, hardware implementation, sensor requirement, cost, efficiency range, and measurability. In Table 2.3.1, MPPT techniques are listed according to their efficiency and the amount of energy they produce.

Table 2.3.1

Ranking of MPPT techniques according to their efficiency

MPPT techniques	Efficiency (%)	Energy production ranking
Incremental conductance	99.48	1
Perturb and observe	99.29	2
Temperature	97.01	3
Open voltage	94.56	4
Short current pulse	90.72	5
Constant voltage	79.51	6

According to the data in Table 2.3.1, it is seen that energy production is superior to other methods and that there is a similar performance among themselves. This result is seen with the widespread use of commercial applications. The incremental conductance method, among other techniques, enables energy with high efficiency to be obtained from PV panels. The output of the incremental conductance method has the same shape as the solar irradiation input, except that it has a small transition time at the time of fast irradiation. As a result, this method adapts to atmospheric conditions faster than others and has a very small response time with very little oscillation in the

MPP. Thus the total amount of energy to be taken from the PV panel increases. The same results are also obtained with a perturb and observe method. The difference between these two methods is that the number of processes used in the incremental conductance technique is slightly higher than the perturb and observe method. Each process causes the hardware and software differences to be used in the system and increases the cost. The incremental conductance algorithm efficiency is the same as that of the perturb and observe method.

The open voltage and short current pulse methods require an additional static switch to the system but still provide much lower energy transfer than the perturb and observe and incremental conductance directions. Loss of energy occurs during switching. Moreover, since the open voltage and short current pulse methods do not make instant time tracking, the solar irradiation change during switching cannot be detected. In fact, these techniques cannot calculate new MPP unless there is a new irradiation level. Furthermore, sampling time selection plays a very critical role for these techniques, since the shorter selection of the sampling time will increase the number of switches, which means that the power generation will be very low. If the sampling time is long, it cannot follow MPP closely in fast changing weather conditions.

Open voltage and short current pulse methods are quite simple, do not require complex circuits, and are cheap and convenient methods. However, it is problematic to remove the PV panel from the load in order to generate a reference mark. In the meantime, the solar energy cannot be utilized and the actual MPPT process that cannot be sustained has negative effects.

The temperature method is providing less energy than incremental conductance technique and perturb and observe technique. Unlike other techniques, irradiation and temperature values are read, but the MPP cannot be fully monitored since only the voltage of the PV panel is read.

The open voltage method is the lowest among the other methods. In fact, this technique does not follow the MPP but instead takes the optimum voltage under the STC or another constant voltage as the reference voltage, keeping it constant under any operating condition.

In terms of cost, MPPT costs are electrical components, electronic components, switchboards, controllers, and number of analog and digital sensors, software applicability and all other power components. The topology of the MPPT applications is largely based on the preference of the end users and is a good option for analog circuits with short current pulse, open voltage,

or constant voltage methods. With the digital circuit that requires the use of processor, the perturb and observe, incremental conductance, and temperature methods can be easily applied. In addition, analog circuitry is less expensive than digital circuitry (processors and embedded systems). This cost comparison calculation is formulated taking into account the current spread of the MPPT methods.

The number of sensors required to implement the MPPT method also affects the total cost. Often, measuring voltage is easier and more reliable than measuring current, current sensors are often more expensive and cumbersome. Solar irradiation and temperature sensors are very expensive and not easily available. After all these cost assessments, Table 2.3 provides a simplified classification of sensors, processors, and additional power components.

Table 2.3.2.

Cost classification of MPPT techniques

MPPT techniques	Additional component	Sensor requirement	Processor calculation
Constant voltage	No	Low	Low
Short current pulse	Yes	Medium	Low
Open voltage	Yes	Low/medium	Low
Perturb and observe	No	Medium	Low
Incremental conductance	No	High	Medium/ high
Temperature	No	High	Medium/ high

Mechanical solar tracking systems. Solar energy is less preferred than other RES because of the high initial cost and low efficiency. Although the installation costs of solar energy systems are high, the operating and maintenance costs are much lower than other energy types. Efforts are underway to increase the efficiency of solar energy systems and reduce costs. The main reasons for low efficiency in solar energy systems are as follows:

- Inability to utilize solar energy continuously due to the solar and earth rotation movements,
- The loss of radiation as the sun rays pass through the atmosphere,
- Maximum efficiency of PV panels occurs only when the solar irradiation

comes upright,

- Inability to obtain desired irradiation in bad weather conditions, and
- Increased cost due to the need for large surface area to obtain high power.

In order to eliminate all these negativities, some efficiency increase studies are carried out. One of these is to ensure that the solar panels can receive the solar irradiation at a right angle. PV panels are designed to be movable and allow the system to follow the sun throughout its movement. A total efficiency increase of 45 % can be achieved with the mechanical solar tracking system. Solar tracking systems are classified into two different ways as single-and two-axis according to the number of axes.

Single-axis solar tracking system Single-axis solar tracking systems follow the solar by moving in a single axis (vertical or horizontal). Generally, the inclination angle is adjusted manually at certain intervals during the year and automatic movement is provided in the east–west direction. Single-axis systems are more cost-effective than two-axis systems but have lower yields in terms of efficiency. Single-axis solar tracking systems are moved on the vertical or horizontal axis depending on the solar trajectory and the weather condition. Fig. 2.3.16 (A) schematically illustrates the single-axis solar tracking following the azimuth angle.

Two-axis solar tracking system. In two-axis solar tracking systems, it is possible to follow the solar with two angle values indicating the position of the solar in the sky. The control system moves on the azimuth and zenith axes. PV panel efficiency can be increased by 30 %–45 % with two-axis control system. The azimuth axis is the axis in which the movement of the PV panel in the east–west direction is adjusted, while the zenith axis is the movement in the north–south direction of the PV panel. In order for the system to follow the solar, the position of the solar must be determined first. In order to realize this work, solar detection sensors are used in the system. The two-axis solar tracking system is given in Fig. 2.3.16 (B).

The solar detection sensor (pyranometer) is synchronized with the control circuit. The information received from the pyranometer is evaluated in the central control unit, and appropriate position signals are sent to the driver of the east–west and position motors to ensure the two-axis movement of the system. Thanks to the position signals, the motor drives drive the motors and ensure the two-axis movement of the PV panel. This movement continues until

the solar rays are perpendicular to the PV panels.

Concentrated PV panels. Concentrated solar panels are based on the principle of more intense collection of solar rays into PV cells. It keeps the peak power of the PV cell constant and ensures maximum utilization of the PV semiconductor field used. With this method, it is possible to harvest 30 times more energy than a low-concentration PV panel and 1000 times more energy than a high-concentration PV panel. Concentrated solar systems need a solar monitoring system. Single-crystal silicon PV panel normally works in 12 % efficiency, when focused; it can work in 20 % efficiency. Concentrated PV panels produce high temperatures due to focus. This heat can be recovered using cogeneration applications. The disadvantage of concentrated PV panels is that the efficiency of the PV cells decreases due to the high temperature. In such applications, PV panels need to be cooled. Concentrated PV panels are in commercial development. Fig. 2.17 is given the concentrated PV panel structure.

Cylindrical PV panels. Cylindrical PV panels consist of cylindrical panels coated with 360° thin PV cells. A reflector is placed on their surface. Thus in addition to the solar irradiation directly exposed during the day, they can generate electricity from the light reflected from the reflector surface. Cylindrical PV panels can be mounted side by side horizontally for optimum energy generation. Cylindrical PV panel systems are lightweight and unlike planar panels, they are not exposed to wind.

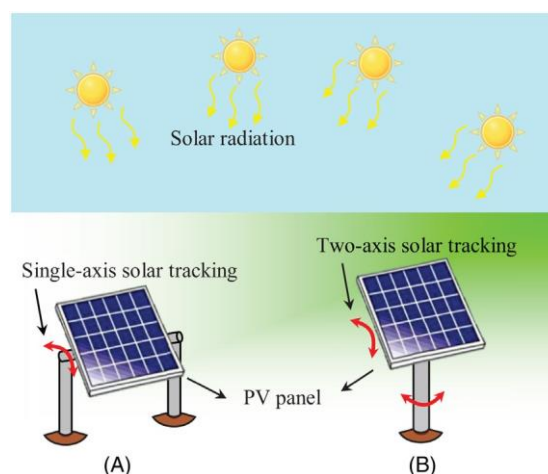


FIG. 2.16. Solar tracking systems. (A) Single-axis and (B) two-axis.

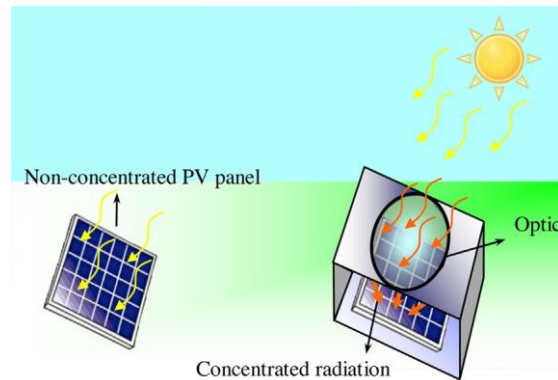


Fig. 2.17. Concentrated PV panel structure.

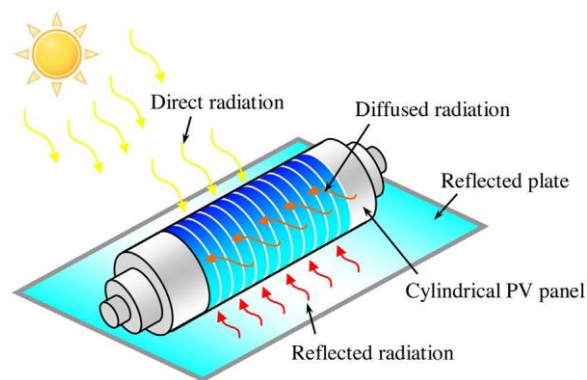


Fig. 2.18. Cylindrical PV panel structure.

Resistance. Therefore weights are not required for the installation of cylindrical panels. In Fig. 2.18, cylindrical PV panel structure is presented.

CONTROL QUESTIONS:

1. How is solar energy produced?
2. How are wind and ocean waves formed?
3. What technologies are used for direct collection of solar energy?
4. What type of diodes are used to convert sunlight directly into electrical energy?
5. Explain the distribution of solar radiation.
6. What materials are used to manufacture solar panels?

7. Which semiconductor elements are most commonly used in solar panel production?
8. How does a photovoltaic power station operate step by step?
9. How does the I–V (Volt–Ampere) characteristic change when panels are connected in series and parallel?
10. How does a central tower solar power system operate?
11. What are the advantages and disadvantages of PV and CSP technologies?
12. What are the advantages and disadvantages of photovoltaic panels?

Chapter III

SOLAR HYBRID ENERGY SYSTEM

3.1. Solar hybrid energy systems

Solar-based renewable energy sources produce output characteristics according to the position of the sun. This characteristic differs depending on the resource type. While the temperature level of the heated liquid varies in concentrated solar systems, there is a change in output current and voltage in photovoltaic (PV) panels. Solar systems are also renewable energy sources that generate energy depending on the solar irradiance. Solar irradiance utilization period is an average of 8–10 hours per day, depending on the region and season. In cases of cloudy and evening hours, the solar energy cannot be used. These problems have revealed the need for “Why solar hybrid system?”. By using another renewable energy source together with solar systems, uninterrupted and continuous electricity generation can be provided. One of the most preferred sources here is wind energy. Wind energy is easy to install and access, just like solar power. Unlike solar energy systems, wind energy systems have a moving structure. Wind formation depends on the temperature changes on the earth’s surface caused by the solar. As a result, wind energy is indirectly dependent on the solar source. Unlike solar energy, wind energy can occur at any time of the day. Wind energy can be used in the evening and at night also, while solar energy is used only during the day. By using wind energy together with solar energy, generation characteristics at different power frequencies can be combined. In this case a solar hybrid energy system is created by combining solar energy with a different renewable energy source. Thanks to the diversity of sources in solar hybrid systems, power generation possibilities can be increased. Despite all this diversity of resources, in order for the energy to be continuous, stable, and of high quality, energy storage units that have a complementary feature come into operation together with renewable energy sources. The cost of energy storage systems increases as the power values increase. Batteries are one of the most preferred methods in terms of usage and ease of purchase. Thanks to technological developments, more efficient and higher capacity energy storage units are produced. As a result of these developments, unit prices of batteries are also falling. Nowadays, thanks to batteries, the concept of the word “mobile” has become an indispensable

part of our lives. Mobile phones, 48 Solar Hybrid Systems computers, tablets, smart watches, household/commercial electronic devices, and electric vehicles are just a few of the examples powered by batteries. Solar hybrid energy system is a combination of energy sources with different characteristics and an energy storage system. In the case of off-grid applications, determining the best combination to reduce the initial investment cost (maintaining power supply reliability, reducing maintenance) in hybrid energy systems is a challenging process for many reasons.

The combination of renewable energy sources with different characteristics reduces the total energy potential effects of sources, the output characteristics of which change over time. Only solar power (PV panel, concentrating solar system) is available during the daylight, but when it comes to night, you have to store energy from the solar power during the day to ensure energy continuity. Wind energy has similar qualities but unlike solar energy, it often has a chaotic possibility. Due to the nature of renewable energy sources, the energy potential that changes over time makes it necessary to combine energy storage systems and distributed energy sources.

Energy generation systems play an important role in daily life. In our daily life, electrical energy is used in many areas and devices and becomes indispensable. Although we use electrical energy every day, unfortunately very few of us are concerned with energy saving. Although we always try to criticize the cost of electrical energy, we have more responsibilities as individuals, especially in terms of social responsibility. Fossil fuel resources are rapidly being exhausted, and many irreversible effects occur due to the burning of fossil fuels. For all these reasons, we are in a period when special attention should be paid to energy saving. The system design and installation phase are vital to obtain optimum benefit from an electrical energy system. A number of techno-economic and environmental aspects must always be considered in this challenging process. Design modeling for such renewable energy systems is often a difficult part. It is important to determine the design parameters before proceeding with system setup. At this stage, optimization of work is required for the renewable energy system and it is necessary to move away from classical methods. Today, there are many hybrid energy systems for commercial and domestic use. Some of those—wind and PV panel energy, biomass and PV panel energy, concentrating solar and fuel cells, PV panel energy and battery, biomass and wind energy, and geothermal and PV panel

energy—are a few examples.

Today, electrical energy has become a global demand. Concerns such as fossil fuel reserves and climate change have prompted researchers to search alternative energy sources. Solar energy is the most acceptable form of all renewable energy sources. Solar energy is a free resource available in every country even individually. The use of solar energy is carried out in two different ways, active and passive. In the active use method, energy is directly converted into electrical energy by using PV panels that have a nonlinear output characteristic. The efficiency of PV panel varies depending on the solar irradiance value, ambient temperature, and PV panel properties. In the passive method the heating/cooling feature is generally used. Passive solar power system is used to heat/cool a living space. Thanks to the passive solar energy system, it is used to reduce energy costs in the field of heating and cooling. In this system a building or an apartment uses solar energy indirectly from this energy. The passive solar energy system contains a small amount of moving parts in the conversion system. These systems are of low maintenance and eliminate the need for externally maintained heating/cooling systems. Passive solar system design and installation is not too complicated. In this system the knowledge of solar angle and climate change is a basic requirement. Passive solar power system can be easily integrated into any building. Different heating methods are provided with passive solar energy system. The first of these is direct gain and, in this method, solar irradiance directly penetrates the building and heat energy is stored. Another method is indirect gain, in which solar radiation is collected, stored, and distributed using a solar wall containing thermal storage materials. Solar wall application topology for summer and winter is given in Fig. 3.1. The solar wall is a very suitable system especially for using in cool but sunny climates. This method is a combined system that heats and cools the air with solar energy. Another method is isolated gain, in which solar radiation is collected and used in a predesigned penable and closed area of the building.

The main purpose of passive solar energy systems is to maximize solar heat gain in winter and to minimize heat gain in summer. In the passive solar system the direction of the building should be positioned facing east to west. Windows, location and size of which are determined at the design stage, are used in buildings to maximize the heat gain from the sun in winter and to minimize the same

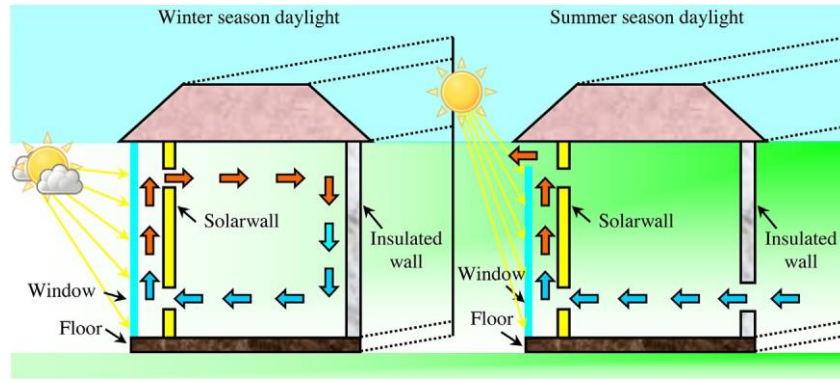


Fig. 3.1.1. Solar wall application topology for summer and winter season.

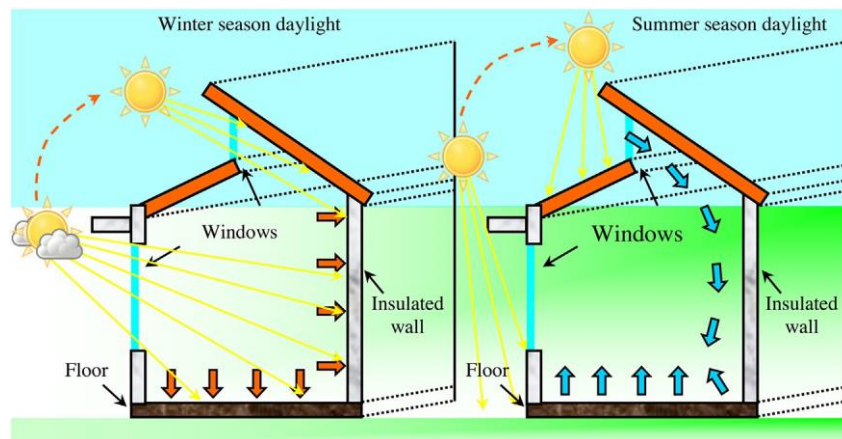


Fig. 3.1.2. Roof and window overhang application topology for summer and winter season.

In summer. The roof and windows overhanging are sized to face south and heat is gained in winter. The roof and window overhang application topologies are given for summer and winter seasons in Fig. 3.2. Thermal mass heat from solar irradiation is stored in walls or floors. Thus daylight is used to provide lighting. With this method the building is effectively cooled with natural air in summer, thanks to the roof and windows overhanging. In passive solar system design, the windows can be opened to clean the air inside at night and closed to meet the cooling requirement during the day. One of the disadvantages of

passive solar system is that its activity lasts only for 16–18 hours per day. Other energy sources should be used for heating/cooling in the remaining time period. However, the passive solar-energy system used for heating/cooling saves a significant amount.

Solar energy is directly converted into electrical energy by using PV panels in active solar energy system. Solar PV panels are produced with silicon-based semiconductor technology. Solar PV cells are commercially available today; these are produced with mono-crystalline, polycrystalline, bar crystal silicon, and thin-film technology. The output characteristics and working principles of solar PV panels are given in detail in Chapter 1, Solar System Characteristics, Advantages, and Disadvantages.

Concentrated solar power plants have large mirror parabolic trough collector areas, a steam generation heat-exchanger system, and Rankine steam turbine generator. A thermal energy storage unit can also be added to these systems upon request. The parabolic trough power system can be used with fossil fuel power plants. The purpose of this type of hybrid system is to reduce the heat loss rate of the plant and to increase the steam cycle, power output, efficiency, and performance.

Linear Fresnel power systems are arranged in parallel rows and generally aligned on the north–south horizontal axis. Parabolic trough solar collectors with single-axis tracking structure are available in large modular arrays. Each solar collector has a linear parabolic-shaped reflector that focuses direct solar radiation on a linear receiver (absorber tube) located at the focal line of the parabola. The collector axis mechanism is to focus on the collectors by following the sun moving from east to west throughout the day.

Thus the irradiance from the sun enables a heat-transfer fluid contained in the linear receiver to be heated to approximately 400 °C (750 °F).

In order for a concentrating collector to achieve high-efficiency energy harvesting, it must focus on the sunlight directly in a plane vertical to the receiver. Due to clouds, moisture, and other particles on the earth's surface, scattering occurs in the atmosphere and the solar irradiance value decreases. In the case of a linear axis trough solar energy system, effective solar irradiance is very important for high performance.

In the concentrated solar energy system, the high heat transfer fluid passes through the receivers as high pressure superheated steam or through a heat exchanger to create a thermal storage system. Superheated steam is sent to the

turbine to generate electricity in a Rankine cycle system. The steam used in the turbine is returned to the heat exchangers with the steam condensation method and turned back into steam. The steam condensation method is carried out with an evaporative cooling tower or directly with an air-cooled condenser. The choice of steam condensation method will affect the total water use in the system, cycle performance, and operating cost. Dry cooling, one of the steam condensation methods, significantly reduces water use but increases investment and electricity costs. The high heat transfer fluid is reheated in the concentrated solar line after passing through the heat exchangers. Molten nitrate salts or compressed gases are used as high heat transfer fluid. The direct steam generation from the concentrated solar line is also carried out in addition to these methods.

Fig. 3.3 shows an example of solar PV panel and concentrated solar energy system realized in Karabük University Energy Systems Engineering Renewable Energy Resources Laboratory. In this study, hybrid electricity generation has been realized with both concentrated solar energy and PV panel.

A unique and most important feature of concentrated solar and power tower installations is their ability to store highly efficient thermal energy. Thus the thermal energy stored in the daylight is used in the evening. For example, in summer, up to 10 hours of electricity can be generated per day by thermal energy storage with solar energy plants. Another approach is to combine concentrated solar energy systems with other renewable energy sources (wind, biomass, etc.). With these hybrid renewable energy sources, solar energy system output is supported in low solar irradiation periods.

Many research and development studies, related to solar parabolic trough plants, are carried out and planned. These studies bring to light collector component improvements, power plant integration and configuration, thermal energy storage systems, cost reduction measures, and performance improvements. Innovative approaches to improve technology are being developed in these areas financed under commercial energy organizations and government programs.

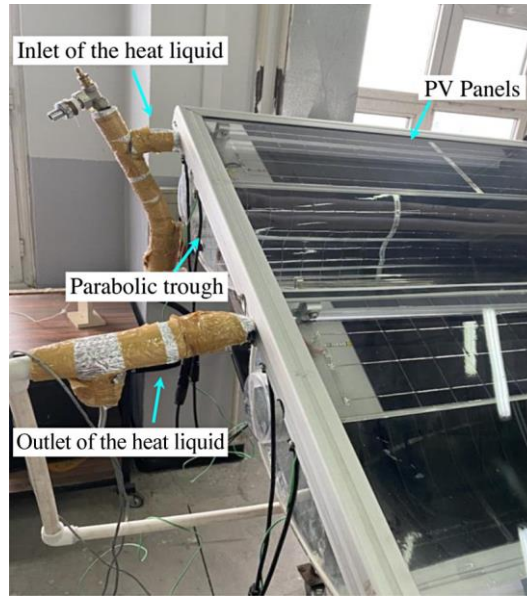


Fig. 3.3. PV panel and parabolic trough hybrid solar system.

In concentrated solar energy systems established with thermal storage systems, the concentrated solar line is enlarged to increase the collected energy. For example, on a sunny day, a high capacity–concentrated solar system may be sufficient to bring the thermal energy storage unit to full capacity. For a specific plant and public application, the concentrated solar system size can be optimized for grid demand model, power demand, and financial parameters.

The main difference between a concentrated solar power system and a conventional thermal power plant is the energy source that depends on natural processes. Although a thermal power plant is ready to be used in the desired period of time, a solar power plant does not have this feature. These factors lead to different methods to measure the steady-state performance of sources.

3.2. Power generated from concentrated solar and PV panels

The thermal power output of concentrated solar energy systems is calculated by configuring a parallel heat-exchanger array. The thermal power that can be obtained from each heat-exchanger array in the concentrated solar energy system can be calculated with the next equation:

$$P_{mes} = mC_p(T_{in} - T_{out}) \quad (3.1)$$

Where P_{mes} is solar thermal power, m is high heat transfer fluid mass

flow rate, C_p is integral average-specific heat of high heat transfer fluid, T_{in} is high heat transfer fluid average bulk inlet temperature to solar heat-exchanger train, and T_{out} is high heat transfer fluid average bulk outlet temperature from solar heat exchanger train.

In a large concentrated solar power plant design, all subunits of the system should be considered. In some cases the high heat transfer fluid is collected to go to the solar steam generator by being heated in a separate subunit. In this case, heat losses occurring in the entrance and exit sections of the pipeline should be taken into account. The efficiency of a concentrated solar energy system is calculated by the next equation:

$$\eta_{mes} = \frac{P_{mes}}{\cos \theta A_{ap}} \quad (3.2)$$

Where η_{mes} is thermal efficiency, $\cos \theta$ is average solar irradiance angle during a test run, and A_{ap} is solar field aperture area in tracking mode during the test.

Solar PV panels are connected in series/parallel to create a PV array. The energy generated by a PV panel is given by the next equation:

$$E_{PV} = SP_f I \eta_m \eta_{PC} \quad (3.3)$$

Where S is surface area of the PV panel (m^2), P_f is packing factor, I is solar irradiance (kWh/m^2), η_{mis} is PV panel efficiency, and η_{PC} is power-conditioning efficiency.

There are usually two or more power conversion units in PV panel-based grid-connected systems. Depending on the current PV panel voltage, it may be necessary to increase or decrease this voltage level. In the first step, there is usually a direct current (DC)/DC power converter unit for making the maximum power point tracking. The alternative current (AC)/DC converter transfers energy to the grid synchronously. In such systems the other DC loads can be supplied with a DC bus. Fig. 3.4. shows the topology of use of a PV panel with maximum power point tracking.

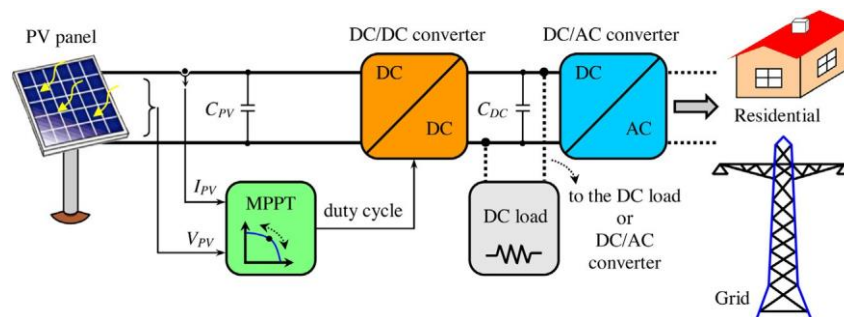


Fig. 3.4. PV panel control and application topology.

Wind energy occurs as a result of the heating of the atmosphere by a small amount of 1 % of the solar energy reaching the earth. The atmosphere does not gain heat evenly due to differences in elevation, geographical shape, position, and sun angle. This causes pressure differences and air currents between regions. As it is known, the air of heat rises and is replaced by air masses at lower temperatures. In this case, wind can be called as air masses that are displaced between high and low-pressure centers due to temperature difference. The greater the difference between these pressure centers is, the larger the airflow velocity will be. Fig. 3.5 shows the wind turbine control and application topology. Wind is a renewable energy source that is domestic, continuous, and clean, does not pollute the environment, and has no fuel–raw material cost due to its direct usability. As a result, the most important contribution of wind turbines to the environment is that it does not generate harmful gases caused by combustion of fossil fuels and does not cause greenhouse effect and acid rain. It becomes reliable and cheaper every day. A wind turbine can be used on average for 20–30 years. This means that after the investment, production can be done without interruption for a long time at a low cost. Wind turbine power plants can be built in as little as 4–5 months. This period can be of 7 years in nuclear power plants, 2–10 years in hydroelectric power plants, and 1 or 2 years in natural gas conversion plants. Considering that wind power plants can easily be transported to different regions, it is seen that these provide quite flexibility in energy production.

Wind turbines occupy less than 1 % of the agricultural land in which they are installed. Therefore wind farms do not prevent the agriculture and livestock activities in the regions where they are established. Wind farms have become economically competitive with thermal and hydraulic power plants. Wind farms enable rural areas with no economic value to be used and create opportunities for regional development by creating employment opportunities. Dismantling costs of wind turbines can be covered by the scrap value of the dismantled parts. In addition, new turbines can be built on farms and production can be continued, if desired, the used areas can easily be restored. Since wind energy can

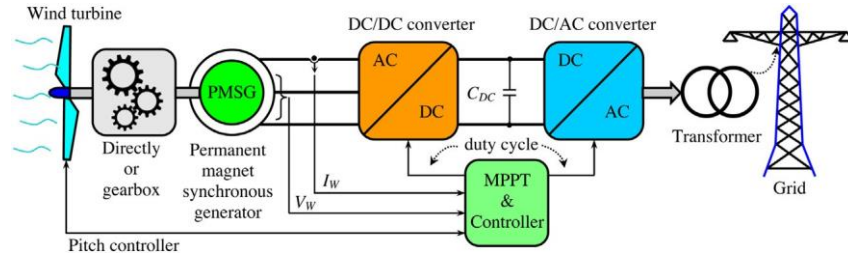


Fig. 3.5. Wind turbine control and application topology.

Be commissioned inexpensively in a short time, it provides supply flexibility. Another important advantage is that there is no need for high network investment to transport the generated power such as nuclear and thermal power plants. Businesses in each region need to build wind farms quickly and avoid extra transport costs. As a renewable energy source without any fuel costs, wind energy is an important alternative to fossil fuels with negative environmental impacts. Under the Kyoto Protocol the use of wind power plants, which cause global warming and climate change, and which do not cause carbon emissions, is increasing in countries that are working on reducing greenhouse gases. Since wind energy has enough potential in most of the world, it will find more usage area in the coming years by using its cost advantage.

The variable wind speed is one of the biggest obstacles of wind power plants. Therefore if the wind is not sufficient at the time when energy is needed, electricity cannot be produced. It has been found that wind turbines can be harmful for some bird species. It is necessary to establish the facilities, considering the migration routes of birds. The noise caused by wind turbines adversely affects the inhabitants of that region. Although wind energy has disadvantages such as damages to the environment, its installation is increasing day by day, thanks to the developing turbine technology. Wind energy makes it more economical and attractive day by day.

The entire wind coming to the turbine blades does not turn into mechanical power in the rotor in wind turbines. For the expression of the mechanical power obtained from the kinetic energy of the wind, the rotor efficiency must be calculated. The amount of air flowing toward the wind turbine is calculated by Eq. (3.4). The actual amount of power captured by the rotor blades is the difference in kinetic energies between the air flows at the wind channel inlet and the wind channel outlet. The amount of power that can

be obtained from a wind turbine is given in Eq. (3.5).

$$m_{air} = A_1 v_{up} = A v_{blade} = A_2 v_{down} \quad (3.4)$$

$$P_{wind} = \frac{1}{2} m_{air} (v_{up}^2 - v_{down}^2) \quad (3.5)$$

Where A_1 is upwind section area, v_{up} is blow-in wind speed, A is blade section area, v_{blade} is wind speed through the turbine, A_2 is downwind section area, v_{down} is blow-out wind speed, P_{wind} is power obtained from the wind turbine, and m_{air} is mass of air.

The wind velocity change along the wind channel to which a wind turbine is exposed is given in Fig. 3.6. While the wind is moving along the channel (wind speed is v_{up} at the inlet and v_{down} at the outlet), it is not in a constant form. Thus the mass flow rate of air moving along the rotating blades (the amount of ass flowing per unit time) can be obtained by multiplying the average velocity by

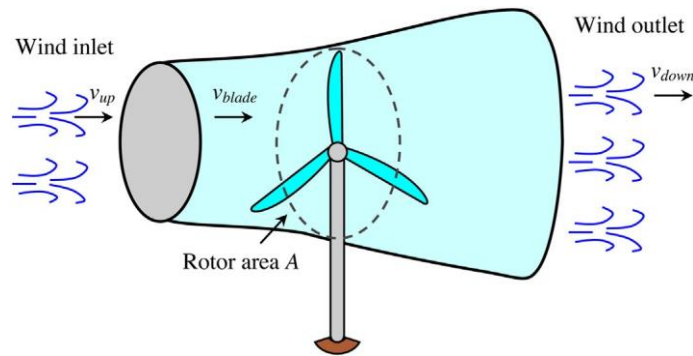


FIG. 3.6. Wind speeds at which a wind turbine is exposed.

The air density. Also, the mass flow rate of air can be obtained by taking into account v_{down} within the rotor sweep area at the rotor plane. The ratio of the wind mass and the generated power relationship is given in Eqs. (3.6) and (3.7). The power value to be generated from a wind turbine using Betz's law is expressed in Eq. (3.8).

$$m_{air} = pA \left(\frac{v_{up} + v_{down}}{2} \right) \quad (3.6)$$

$$P_{wind} = \frac{1}{2} \left(pA \frac{v_{up} + v_{down}}{2} \right) (v_{up}^2 - v_{down}^2) \quad (3.7)$$

$$P_{wind} = pA v_{up}^3 C_p \quad (3.8)$$

Where p is air density, A is section area, and C_p is Betz's law.

Energy storage applications can provide a wide range of benefits to electricity grids and consumers. These advantages include benefits of electricity grid supply, operations and infrastructure, end consumer, and renewable energy source. In addition, energy storage benefits can be grouped as energy oriented, capacity oriented, and bulk power or distributed. There are two general benefits of using energy storage as a resource. These are electric energy is time shifting, and electric resource capacity. When the value or price of electrical energy is cheap, storage is performed. The stored energy is used during the time period when the electricity value or price is high.

Gross benefit refers to total earnings regardless of costs. The net benefit is the difference between the gain and cost. There are three forms of cost prevention. To explain them with examples, the first one is the direct income from energy sales. If storage is located on a larger scale at the level of generation, transmission, and distribution, it may prevent additional investments that may be needed in terms of the generation, transmission, or distribution capacity of the grid. If energy storage is used as an end consumer product, the purpose may be to reduce the electricity bill and/or use it as an uninterruptible power supply.

Sometimes it is appropriate to combine the benefits of multiple storage applications. In such cases the cost and payback period of the system may be more advantageous by combining the benefits of the systems used together. In some cases, only one system may be economically feasible. However, it is often necessary to use several systems together in order to exceed the total costs of the total benefit. In this way, in applications where different systems are used together, technical and operational characteristics should be ensured in terms of benefits. In other words, systems can be used together in order to provide the intended technical benefits and to respond to the operational characteristics required to achieve these. It is possible to face some difficulties when talking about energy storage benefits. The reasons for this may be the lack of sufficient experience and the difficulty of providing quantitative data for the assessment of the benefits mentioned. For example, the use of energy storages can contribute to reduction in emissions from electricity generation, but there are no precise cost assessments that reflect pollution values in electrical generation. The use of energy storage can also reduce fuel consumption for the end consumer (when used in place of the generator), but from the end consumers' point of view, the benefit provided

here can be seen as insignificant. Nevertheless, when distributed, individual energy storage applications are considered as a whole, the effects of which cannot be clearly expressed in this way; it can be seen that significant benefits are provided on a large scale by the grid operator.

The transmission of power and energy in electrical grids is not just a simple task of the system. There are many auxiliary services required for reliable, stable, and efficient operation of these processes. Auxiliary services aimed at achieving the balance of energy supply and its demand at the minute and hour levels are also the basis for ensuring the frequency stability of the enterprise. It can also meet the grid voltage stability and voltage quality requirements with energy storage.

In the provision of auxiliary services, energy storage applications can offer a more technically and economically efficient application compared to traditional fossil fuel power sources. There are two main reasons for this; first, the response times of the energy storage applications can be very short, and the input and output values can be controlled very quickly, thanks to the power electronics circuits. Due to these properties, energy storage systems show a characteristic suitable for use as a power source in auxiliary services. Finally, energy storage systems are more durable than conventional power systems in terms of life according to the amount of change in input and output values. While energy storage applications can more easily respond to different power demands, traditional generation units are efficient and economical only when operated with constant power at their nominal value. If energy storage applications work outside of nominal values, an inefficient operation occurs, energy costs increase, operating life may be damaged, and negative environmental impacts may increase. In terms of auxiliary service, energy storage applications can prevent the need for additional generation, thus eliminating the burden of conventional power plants. If additional generation needs are met from energy storage units, energy costs can be kept constant and adverse environmental impacts and inefficient operating conditions are avoided.

3.3. Use of solar hybrid systems

The purpose of a solar hybrid renewable energy system is to ensure the continuity of energy and to provide higher energy production. A hybrid structure can be created by combining solar-based renewable energy sources

(e.g., PV panel and concentrated solar plant). But the problem here is that the source of both power generating units is solar. In such a hybrid renewable power generation system, energy generation will not occur when there is no solar. In order to eliminate this shortage, it is necessary to use other renewable energy sources. Therefore, the expression of “solar hybrid systems” does not only include solar-based renewable energy generation units but also involves using it together with power generation and energy storage units such as wind, tidal, geothermal, biomass, battery, ultracapacitor, and flywheel. The utilization topology of solar hybrid renewable energy sources is given in Fig. 3.7. Alternative energy sources can close this gap when there is no solar energy. Feeding a building or facility with 100 % renewable energy source can only be possible with hybrid renewable sources and energy storage units. The more the types of renewable energy sources are, the higher the energy harvest probability ratio is. The power generation units increase when the variety of renewable energy sources is high. This diversity of resources aims to control the entire system in an optimum way. Each power generation unit, energy storage unit, and demand unit must be controlled. Energy management algorithms are needed in such hybrid renewable power generation systems so that the end user can reach high quality and continuous energy. Fig. 3.7 shows the hybrid renewable energy sources such as solar PV panel, concentrated solar energy, wind, and other renewable energy sources (off-shore wind, marine current, tidal, hydroelectric, geothermal, and biomass). There are batteries, thermal energy storage, hydrogen, and other energy storage technologies (pumped hydroelectric, flood batteries, compressed air, ultracapacitor, and flywheel) as energy storage units. As the end user in the solar hybrid renewable energy system, all power generation units are combined in the common AC line. There are different energy conversion units for each unit. The DC electrical energy taken from the solar PV panels is connected to the DC/DC

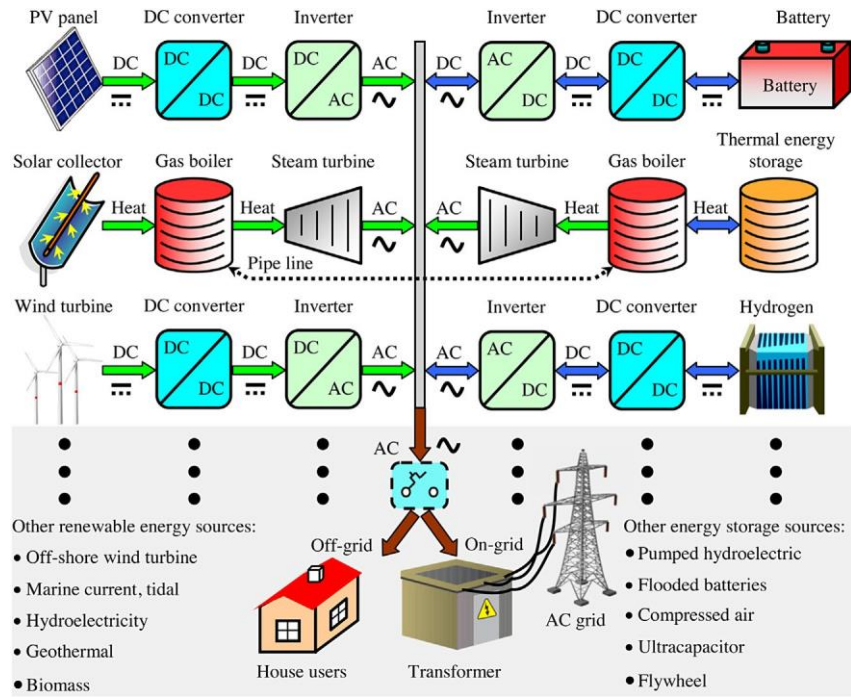


Fig. 3.7. Topology of using solar hybrid renewable energy sources.

Converter and then to the AC line after the DC/AC inverter unit. These subunits are designed to take maximum energy from the renewable energy source. For example, maximum power point tracking method is used in order to get maximum power from solar PV panels, while concentrated solar power system aims to direct solar irradiance to the collector tube located in the center of the reflective mirrors. The subunits seriously affect the total amount of energy to be taken from the whole system in hybrid power generation systems. Therefore each energy converter unit must work with maximum efficiency. In addition, energy management methods are required to control the total energy taken from the hybrid power generation system in an optimum way. In addition, energy storage systems are a complementary factor in the case of excess or lack of power produced by renewable energy sources. Energy storage units have their usage purposes depending on their different output characteristics. For example, batteries usually store the energy when there is an excess of energy in renewable energy sources. Batteries are the most suitable solution to long-term energy demand. However, ultracapacitors can meet the sudden energy demand needs. This energy storage unit preference should be chosen according to the usage purpose of the system. Fig. 3.8 shows a PV panel output graph with an installed power of 5 kW. These power values were obtained from a hybrid renewable energy system with

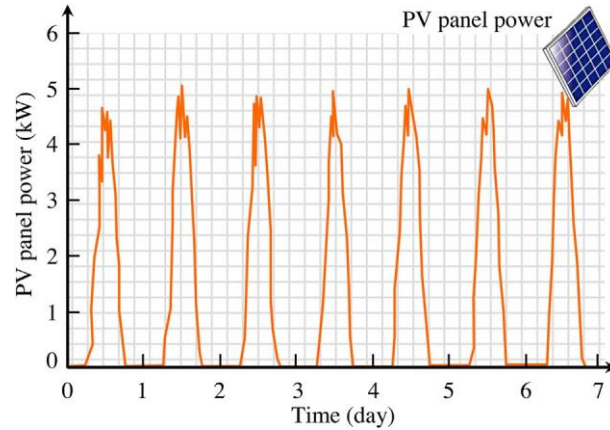


Fig. 3.8 One-week PV panel output power.

An installed power of 5 kW at Kütahya Dumlupınar University in July 2020. When this 1-week PV panel power graph is analyzed, it is seen that daily sunlight time is close to the total installed power. The average daily output PV power is 3.5 kW (for 8–10 hours). In the power graph, it is understood that there is no daily clouding and a stable output power is obtained. The system has an average of 8–10 hours of sunlight duration in the power graph taken from PV panels. While there is energy production during the daytime, it cannot be produced at night. Generating power at the same power value every day shows that the system is steady. However, when looking at night hours, it reduces the continuity of the energy produced by the solar PV system. This situation arises due to the nature of renewable energy sources. Fig. 3.9 shows a wind turbine output power graph with an installed power of 6 kW. These wind turbine power data were recorded at the same time periods

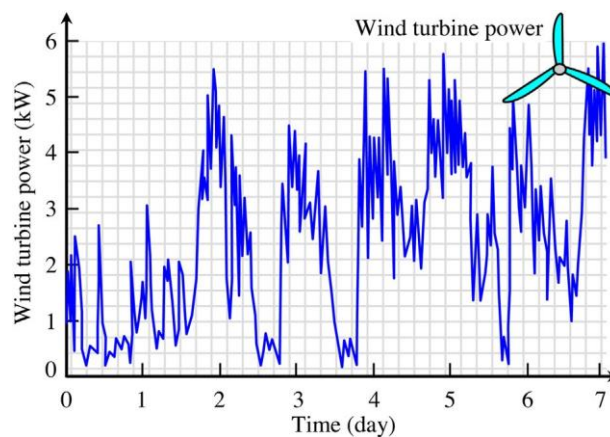


Fig. 3.9 One-week wind turbine output power.

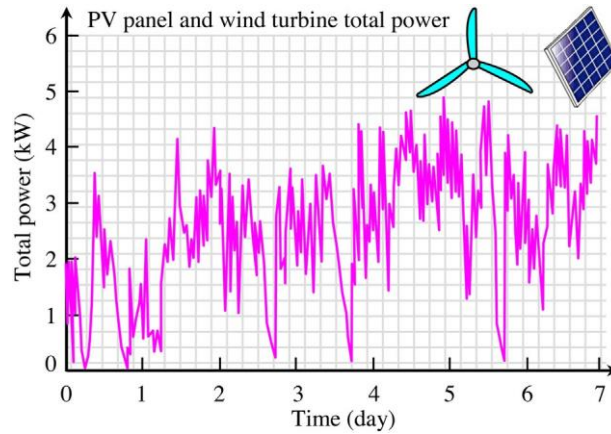


Fig 3.10 One-week PV panel and wind turbine output power.

With the PV panel power. Compared to the PV panel power graph, there is no steadiness and continuity in power generation. Wind turbine power data by nature have a cumulative total power value. The wind turbine power graph realizes a production in high frequency ranges according to the power of the PV panel. In the first 2 days of data acquisition, the power value of 3 kW could not be exceeded. But power graph shows that wind turbine power can be generated even at night. These rapid and sudden changes in power data allow the wind turbine power data to be interpreted over the cumulative total power. The cumulative average daily power value obtained from the wind turbine power is 2.1 kW (for 24 hours).

Fig. 3.10 shows the graph of the total power obtained from a weekly PV panel and wind turbine. When this total power graph is analyzed, a renewable power generation system with a hybrid structure is more stable than when used alone. Considering the total power value, it has the characteristics of both the sources. The oscillation of the power value at high frequency is due to the output characteristic of the wind energy. However, considering the daily average power value, there is a total generation of 3.1 kW (for 24 hours). This power graph reveals the necessity and contribution of using renewable energy sources together. Adding another renewable energy source based on load demand power optimization will increase system performance.

A structure different from the conventional grid structure occurs in hybrid solar energy production systems. Renewable energy sources in more than one building or institution and their integration are one of the important issues. These innovative grid structures are called microgrids. Microgrid is the system where energy is generated locally to meet local energy demands.

While a microgrid can be applied to a small energy-demanding unit, it can also provide energy to large communities such as towns, villages, and islands.

In microgrids, only electrical energy is not produced and used. A cogeneration plant can also be established with the heat energy generated on-site in microgrids. Thus it becomes possible to meet the heating demands of the users as a by-product of electricity generation.

Microgrids are traditionally independent of the centralized grid and can be thought of as a separate entity. However, microgrids can be connected to the central grid to allow the import and export of electric energy generated by renewable energy sources. Thus while microgrids sell their energy remaining, it allows them to be seen as a highly reliable power source as they can generate energy locally whenever possible. Microgrids transfer energy to the grid when there is an excess energy and draw energy from the grid when there is a local power demand. In addition, microgrids use storage technologies such as batteries, ultracapacitors, and hot water storage systems to increase the efficiency of the energy produced. Therefore microgrids are seen as one of the most important developments in future energy generation. The energy management unit in microgrids is one of the most important parts of a hybrid renewable energy system.

The energy management unit allows the energy produced by the resources to be used in an optimum way. The energy management unit constantly checks the energy storage units and ensures that the storage units are always full.

Many methods have been developed with the energy management unit. One of them is the advanced hybrid energy management system. The ideal item-element extension method, fuzzy-logic judgment method, analytical hierarchy process method, gray clustering method, and geographic information system methods are used in the hybrid energy management system. This method provides a convenient use with an interface in a system with two or more power generation and energy storage units at the same time. The user is informed instantly and the possible failure conditions of the units (production or storage unit) are given with this interface. In addition, this interface allows the analysis of how much power renewable energy sources generate and historical data. It enables one to make a prediction about the hybrid power generation system with these data. Thus it ensures that the energy management unit becomes even smarter and ensures optimum

operation.

The renewable solar/wind energy industry is developing rapidly in developing countries. However, the difficulty in selling the generated electricity to the existing electricity grid due to instability and interruptions in electricity supply is a serious problem. In order to overcome these problems, it is especially necessary to solve the issue of generating renewable energy with unstable output power characteristic. This solution is utilized to install hybrid renewable energy systems. Improvising and applying different methods to generate and use the energy obtained in the hybrid renewable power generation system will increase the system cost. In addition, it will affect the depreciation period of the hybrid system and cause unnecessary investment. To solve this problem, it would be wise to add an energy storage unit to the system at the required power level. This will increase the reliability of the hybrid power generation system. Thus the total cost of the hybrid power generation system for energy production at the same power values can be reduced. Adding another source to the hybrid power generation system can provide a solution. The parameter to be considered here is the total demand power of the users. Choosing the right sources with power size optimization in the hybrid power generation system will reduce the capital cost. Producing hydrogen in the hybrid power generation system created by using PV panel and wind energy together is another perspective on storage methods. The hydrogen can be stored with the excess energy in the hybrid power generation system. Later, when there is an energy demand in the system, the stored hydrogen energy is converted into electrical energy and the demand power is met. Hydrogen is not a natural fuel but a synthetic fuel that can be produced from different raw materials such as water, fossil fuels, and biomass. During the hydrogen production phase, there are many alternative hydrogen generation technologies such as steam recovery, waste gas purification, electrolysis, photo processes, thermo chemical processes, and radiolysis. The produced hydrogen can be transported over great distances by pipelines or tankers. The absence of barriers to the transport of hydrogen will enable greater use. Hydrogen has the highest energy content of all known fuels with a value of 120.7 kJ/kg per unit.

Hydrogen can be liquefied at $-252.77\text{ }^{\circ}\text{C}$, and the volume of liquid hydrogen is only 1/700 of its gaseous volume. A hybrid power generation system, included with concentrated solar energy and wind energy, was

established using hydrogen production method in an energy storage unit. This hybrid structure contributed energy to the electricity grid with the use of proton exchange membrane electrolysis in system. The energy management algorithm has enabled the flow of energy by operating the multilevel inverter. Hydrogen is produced by the hybrid power generation unit and stored in a pressurized tank. In the case of need in the hybrid system, it provides energy through the hydrogen fuel cell and the DC/DC power converter circuit. The use of hydrogen as an energy storage unit has gained a commercial dimension with the increase of such applications. This hybrid renewable energy technology enables environment-friendly energy production for 24 hours with its clean energy generation feature. And the same systems are the most suitable solution for small electricity grids and off-grid systems. By definition, “hybrid power generation” is a system that overcomes problems when a single energy source is not sufficient. The hybrid renewable energy system is the sustainable and ecological energy generation method of the future. The significant contributions will be made to the protection of nature with these power generation methods. In addition, hybrid power generation systems will reduce transmission costs in the current grid structure.

CONTROL QUESTIONS

1. What type of energy source is the solar system considered to be?
2. What is the average number of hours per day that solar radiation can be used?
3. When is it not possible to use solar energy?
4. How is a solar hybrid energy system created?
5. In how many ways can solar energy be utilized?
6. What are the disadvantages of a passive solar system?
7. How can a building or facility be supplied with 100% renewable energy?
8. What is a microgrid?
9. How does a microgrid operate?
10. What type of fuel is hydrogen considered to be?

Chapter IV

HYBRID RENEWABLE GENERATION SYSTEMS

4.1. Hybrid renewable energy systems

It is observed that the interest in renewable energy sources has been increasing recently. Renewable energy sources are nonpolluting and easy to access. Such advantages make them attractive for many applications. Today, hybrid renewable energy sources are created by combining more than one renewable energy source. The most widely used wind turbine and photovoltaic (PV) systems are used in various applications such as pumping water, lighting, telecommunications, and providing the electricity needs of remote areas. Hybrid renewable energy sources are preferred for systems that need to be located in remote areas such as wireless telecommunications, satellites, and ground stations. As the demand for renewable energy generating systems increases, research and development studies with these sources continue rapidly.

Solar PV panels or wind energy can be considered as a suitable solution for regions far from the city center. Battery energy storage units are generally used with such systems. These alternative solutions are generally classified as hybrid renewable energy systems. These systems are widely used and preferred in areas where there is no grid structure, because it is much lower than the cost of withdrawing a grid line. The use of more than one source and especially with energy storage units increases the reliability of such systems. Thus the necessary electrical energy of a house can be met by these hybrid renewable energy sources. With the increasing applications of such hybrid systems, system topologies also change. Hybrid systems can be classified as serial hybrid energy systems, switched hybrid energy systems, and parallel hybrid energy systems.

All energy sources feed a battery group in the structure of serial hybrid renewable energy system topology. Each renewable energy source has a separate battery charge control unit. In this topology structure, all units are collected in a single direct current (DC) bus. For this reason the voltage and current parameters of all sources should be sized according to the common DC bus. Power

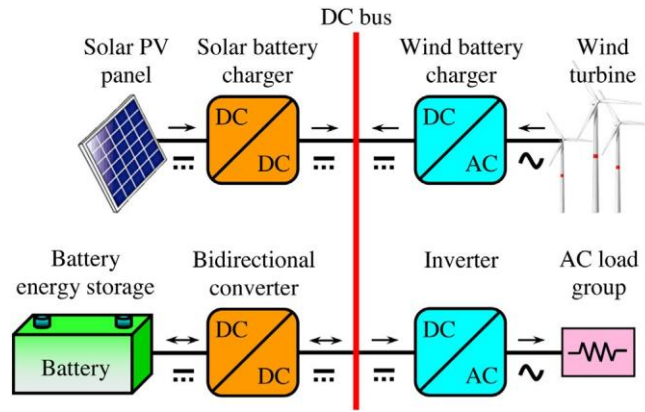


Fig. 4.1. Serial hybrid renewable energy system topology.

Converters in renewable energy source types have the feature of working at the maximum power point. In this topology structure the battery group is always active. For this reason the deep of discharge and cycle life of the battery group should be high. The DC voltage taken from the DC bus is converted into alternative current (AC) voltage with an inverter. In this topology structure the system efficiency is low since the power in all sources is converted to AC voltage with a high power inverter. The serial hybrid topology sizing is determined according to the load power requested by the system. Serial hybrid renewable energy system topology is given in Fig. 4.1. Since there is more than one power generation unit in this topology, the battery group is not exposed to high discharge currents while feeding the load group. Thanks to the common DC bus, different renewable energy sources can be integrated into this topology. In addition to all these, there is a single inverter in the system to feed the load group. The inverter must have the capacity to meet the peak load demand in the system. Since the battery group is exposed to a high cycle number, its life is shortened. In addition, the battery group must have a deep of discharge feature.

Although the switched hybrid renewable energy system topology has application difficulties, it is one of the most preferred structures. In this structure, it is not possible to operate the energy sources connected to the AC bus in parallel. Wind turbine and solar PV panels charge the battery group. In this topology structure, the load group connected to the AC bus can be fed, thus reducing the number of converter units in the system. This structure increases system efficiency. In this structure the units on the AC bus and the battery group can also be charged. This structure enables DC loads to be operated in the system. As in the serial topology, it can meet all the powers in the inverter system. System

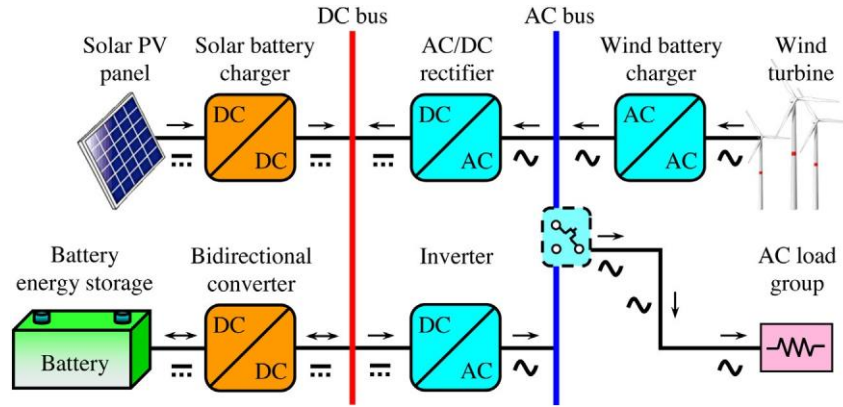


Fig. 4.2. Switched hybrid renewable energy system topology.

Efficiency increases as power conversion units decrease between energy generation units. In this topology, suddenly power cuts may occur during transitions and this is an undesirable feature. Switched hybrid renewable energy system topology is depicted in Fig. 4.2.

Parallel hybrid renewable energy system topology includes both DC bus and AC bus. Renewable energy sources generating DC power are collected in a single DC bus. Units with AC output characteristics are collected in the AC bus. Bidirectional inverter is used between these two buses. This bidirectional inverter operates in AC/DC rectifier or DC/AC inverter mode according to battery and load demand power. If the energy produced by the AC power generation units is equal to and greater than the energy demanded, the load group is fed by the AC bus. The battery group is charged with the excess energy bidirectional inverter in this power generation unit. If AC power generation systems cannot meet the load demand, the battery group is activated. In this case the bidirectional inverter meets the energy requirement of the load group. The role of the bidirectional inverter is great in this topology structure. The power capacity of this bidirectional inverter must be high. If the bidirectional inverter faults, the energy units on the DC bus side are canceled. Since the bidirectional inverter operates in both rectifier and inverter mode, it reduces converter units. The reduction in power converter units increases system efficiency while reducing cost.

Parallel hybrid renewable energy system topology has many advantages compared to other topology structures. In this topology structure, each power converter can be controlled from a single unit. This hybrid energy management algorithm ensures optimum use of energy. Although these

control structures

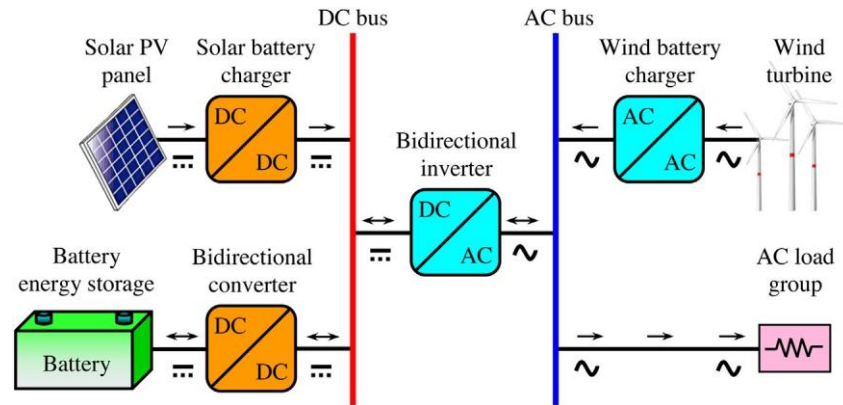


Fig. 4.3. Parallel hybrid renewable energy system topology.

The efficiency, cost, and control unit selection are important criteria in the sizing stage of hybrid energy systems. Before proceeding with such hybrid power applications, simulation programs will help one to make the right decision. The purpose of energy management algorithms is to provide optimum operation for the whole system. These control algorithms also ensure that the energy obtained from renewable energy sources is at the maximum level. The hybrid energy control unit aims to ensure that the cycle life of the elements in the system exists as long as possible. The energy management algorithms control the charge/discharge rates, deep of discharge current and cycle life numbers of the battery group. The more parameters related to the battery group are evaluated, the longer the battery will be used. On the other hand, this situation makes the controller more complex. The complex structure of the control unit increases system reliability. The fluctuating output power characteristics of renewable energy sources are detected by the control system and the battery group is activated. The hybrid energy control algorithm must continuously respond to changing conditions by the system.

If the demand load power in the hybrid system is supplied by energy sources, the most efficient operation situation is achieved. Thus the charge/discharge cycle of the energy storage unit is reduced. The most efficient control method selection depends on system components, environmental conditions, maintenance period, and operating modes. Grid-connected hybrid energy system topology is given in Fig. 4.4

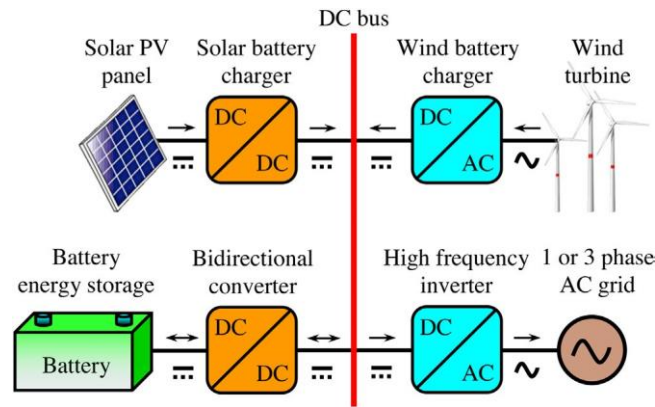


Fig 4.4. Grid-connected hybrid energy system topology.

Using more than one renewable energy source and energy storage unit together increases the reliability of energy. Using these systems synchronously with the grid ensures that the energy is used uninterruptedly. Grid-connected hybrid renewable energy systems are usually connected to the grid with low-or medium voltage. The inverter in the hybrid power generation system is used by connecting to the grid synchronously. High power applications are usually connected to the medium voltage grid by a transformer. Since this transformer has high power, its dimensions, weight, and cost are also high. Thanks to advances in power electronics, inverters can be directly connected to the grid. Isolation between the hybrid system and the grid is also provided by a transformer. However, this transformer has very low dimensions and weight thanks to its high-frequency structure. While transformers working with low frequency (50–60 Hz) in the classical method, they work with 10–20 kHz in new-generation inverters. Electrical isolation is provided in both usage methods. In such applications, renewable energy sources are combined in a single DC bus. By using high-frequency inverter between the hybrid system and the grid, both grid integration and electrical isolation are provided.

When renewable energy source types are used for distributed energy generation, each source has some disadvantages of its own nature. As a popular solution to eliminate these disadvantages, hybrid systems are often created. For example, in wind energy, the power is generated during the wind blows; in solar PV panel energy, the power is generated during the daytime and a sunny time. PV systems have a modular structure. It allows for a new solar PV panel to be added to the system if more power generation is

demanded from solar system. Although the level of solar irradiation and insolation varies according to the region, season, and time of day, sunlight is one of the energy sources that

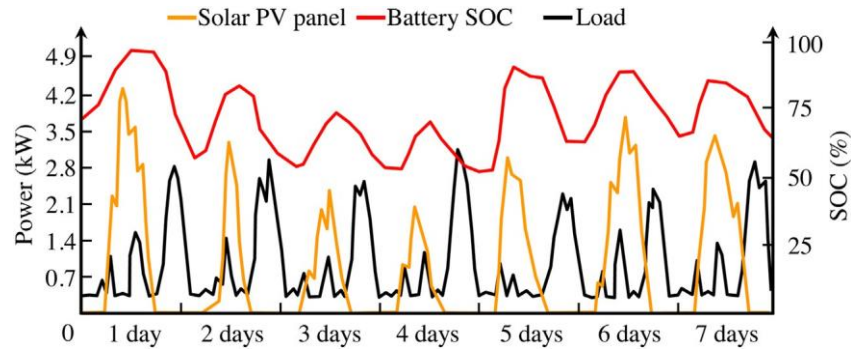


Fig. 4.5. The power generation graph of solar PV panel system with energy storage.

Can be found almost everywhere on the planet. However, the onset of winter or cloudy periods in many places limits the availability of sunlight. When the time interval needed by the load and the energy generated from the solar system do not match, the excess energy generated during intensive use is usually met by an energy storage system. The need for a large energy storage capacity can significantly increase the cost of the system. Usually, a backup electric generator or an external grid is required to ensure continuous availability, which means higher costs. A 20-kWh capacity energy storage unit has been connected to the solar PV panel system with a power capacity of 5 kWp. Fig. 4.5 shows the battery group state of charge, load group power, and solar PV panel power on a weekly basis. Fig. 4.6 shows the data of a 5-kWp solar PV panel power output graph for 2019 in Kütahya Dumlupınar University Electrical and Electronics Engineering Department. A total of 6.2 MWh of electricity was generated throughout the year of 2019 with this solar PV panel system. As can be seen in the power generation graph, power generation peak values vary depending on the seasons.

4.2. Hybrid system: Photovoltaic panel, Wind and Battery

The wind data were analyzed for the same area where the solar PV panel is installed. Coordinates of the location where the wind data are analyzed; latitude 39.11° and longitude 29.01° . Wind data have been obtained over the National Energy and Climate Plans (NECPs) at hourly intervals since 1979 until today. These data include wind speeds, wind directions, air pressure, and air temperatures. Wind data results have been obtained for the region below 10

m. The coordinates determined in the Navi onics Boating program were used in the NECP program, and the requested data were made ready for processing. After the transfer process the data divided on a monthly basis were processed separately and as all data. First of all, all 40 years of data were processed and the wind rose profile at the selected point was created. As a result of this process,

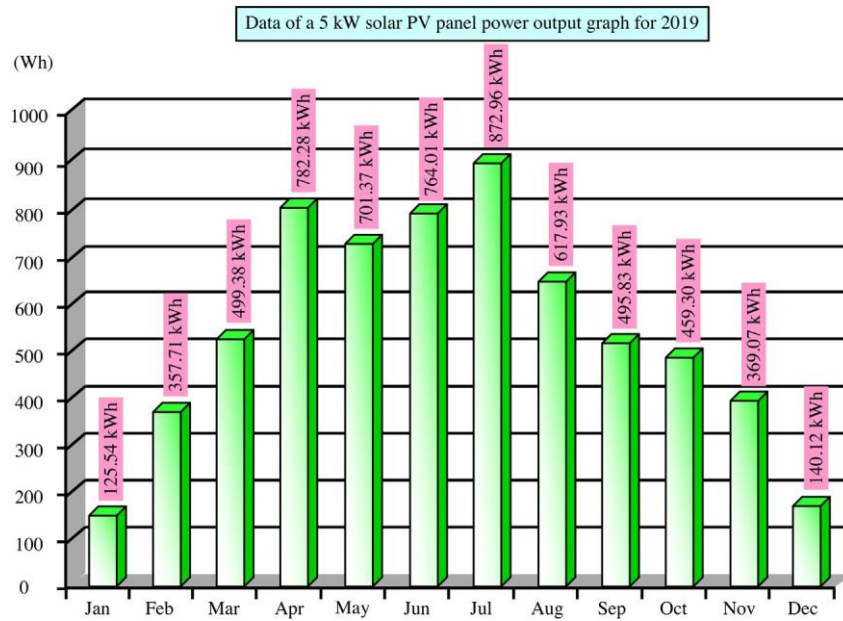


Fig. 4.6. Data of a 5-kW solar PV panel power output graph for 2019.

The expected profile has been obtained. It has been observed that the northeastern winds are dominant. All 40 years of data are divided into 16 directions in the design of wind rose. The wind speeds by months are given in Fig. 4.7. The all speed data of the wind rose are given in Fig. 4.8. The process of obtaining wind rose was repeated by filtering 40-year data for all months on a monthly basis. As a result of this process, it was obtained both a wind rose consisting of all data and separate wind roses for 12 months. When the monthly average wind speeds are analyzed, it is clearly seen that the northeastern and southwestern winds are dominant in the winter season, while the northeastern wind is dominant in the other seasons. Energy generation times can be determined by processing the minimum and maximum wind speeds required to generate wind energy from the graphics obtained.

The energy continuity curve has been calculated in two separate ways for all wind data and speeds between 2 and 15 m/s. Unfiltered energy continuity curve obtained for all data is given in Fig. 4.9. The energy continuity curve

obtained for filtered data is given in Fig. 4.10. The wind roses on a monthly basis show that the winter season is formed on the southeastern axis, and the other seasons are predominantly on the northeastern axis.

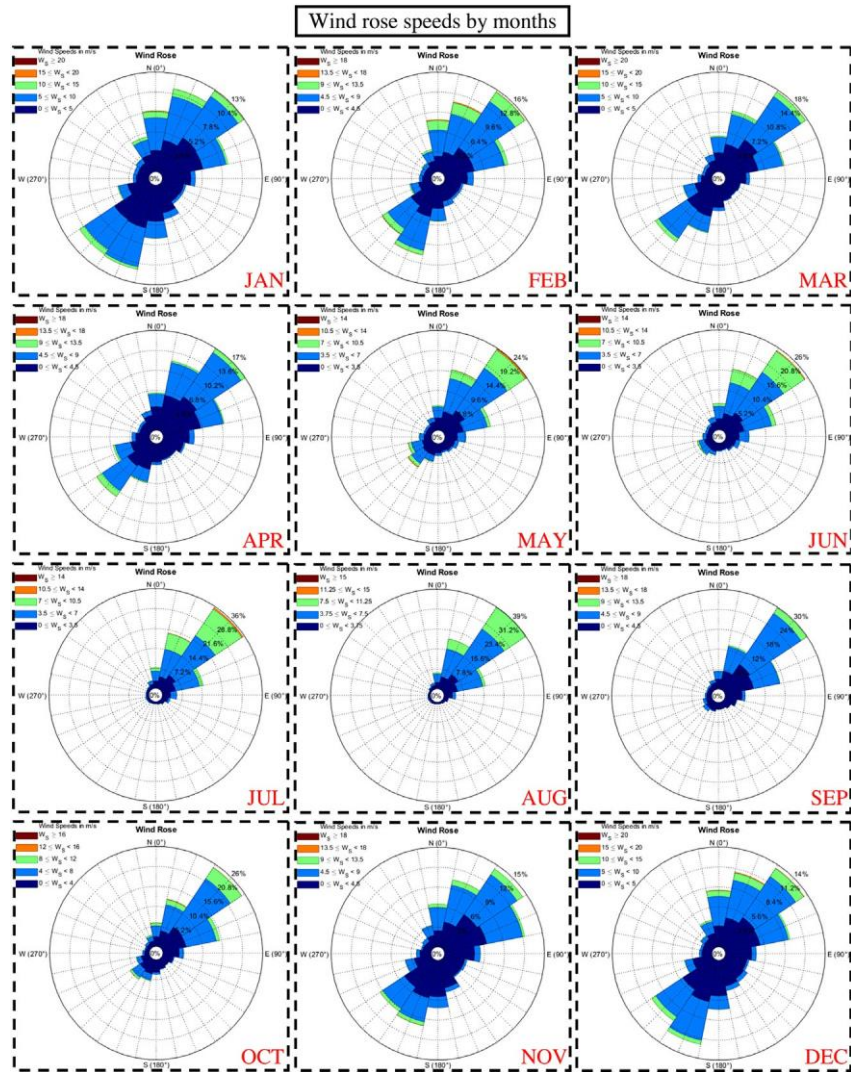


Fig. 4.7. Wind rose speeds by months.

For the wind energy conversion efficiency, the cut-in and cut out speeds of the horizontal axis three-bladed turbine were calculated by filtering. Applying. That the three-bladed turbine can generate energy at a minimum of 2 m/s and a maximum of 15 m/s, all speeds outside this range are taken into account as 0. Wind data have been analyzed for the date of July 18, 2019. The power chart of a 1-day 5-kWp capacity turbine is given in Fig. 4.11A. Typical year-round hourly, daily, and monthly power analysis was performed for 2019. Typical year-round hourly, daily, and monthly power data graphs are given in Fig. 4.11B, C, and D, respectively. Wind speed values are grouped and

averaged separately for each month. A typical monthly average efficiency column graph is given with

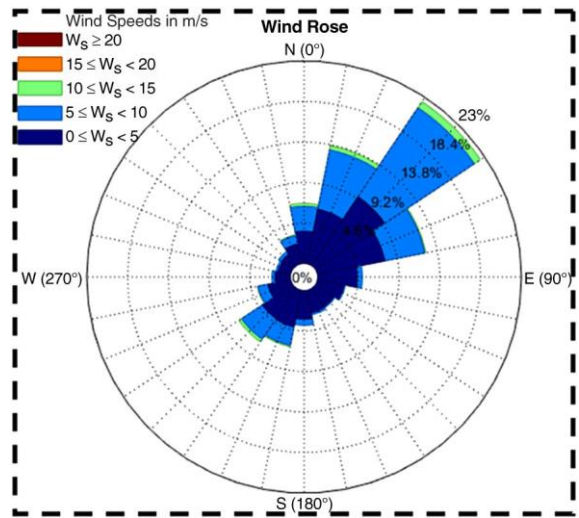


Fig. 4.8. Wind rose speeds (all data).

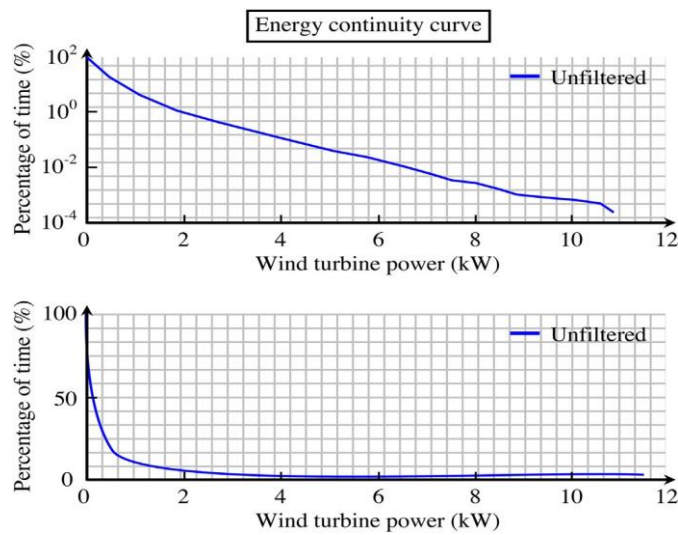


Fig. 4.9. Unfiltered energy continuity curve.

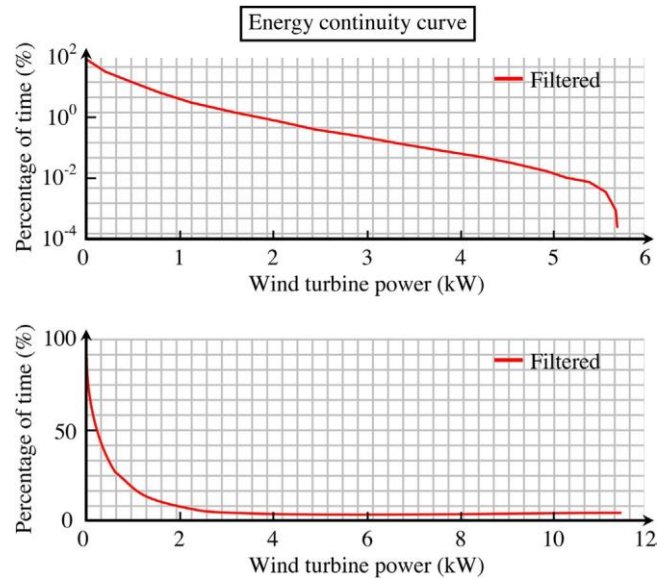


Fig. 4.10. Filtered energy continuity curve.

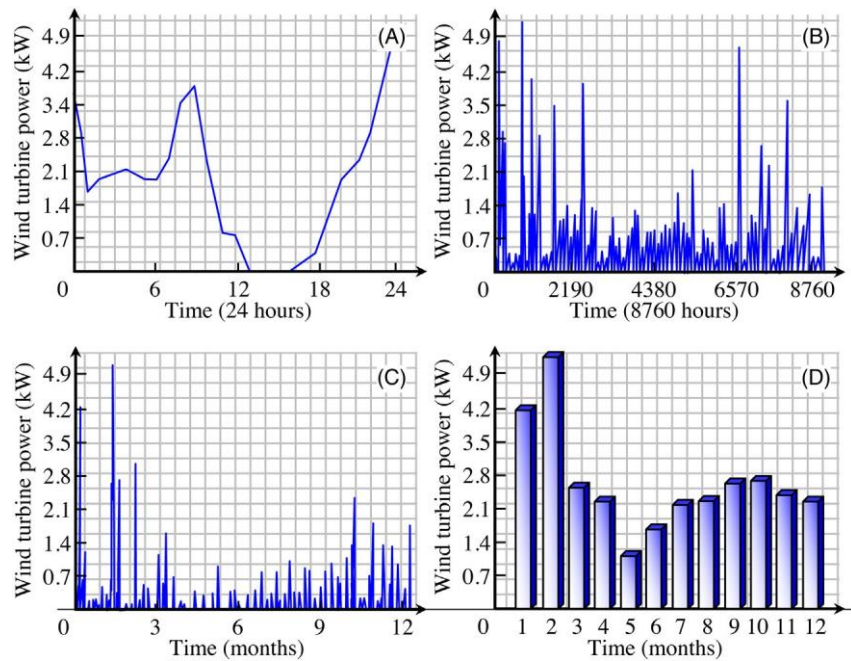


Fig. 4.11. Graph of 5-kW wind turbine output power. For 24 hours, (B) typical year-round hourly efficiency, (C) typical year-round daily efficiency, and (D) monthly average efficiency.

Like sunlight, wind is a free and nonpolluting source of energy. However, noise pollution should be considered in larger turbine models. Although it varies dramatically with wind speed, region, and other environmental characteristics, it can be found everywhere at a certain capacity. However, off-grid wind systems experience similar challenges to solar PV panel systems. Wind

speeds head to fluctuate significantly from 1 hour to the next and from one season to the next. Unexpected delays may occur in the energy produced. Renewable energy sources cannot continuously generate energy throughout the year and cannot meet constant load demands. As with solar PV panel power, an energy storage or backup power supply is required to provide uninterrupted power.

When both solar and wind energy are integrated into a hybrid generation system, they have significant advantages over their counterparts alone. Most importantly, a hybrid use of wind and solar energy can create less fluctuations in the energy produced by the system. This increases overall energy output and reliability and reduces energy saving requirements and associated costs.

A weekly power output graph created by using solar PV panel and wind energy system together is given in Fig. 4.12. Solar PV panel and wind energy production are very low at night. During these time intervals, it seems that en

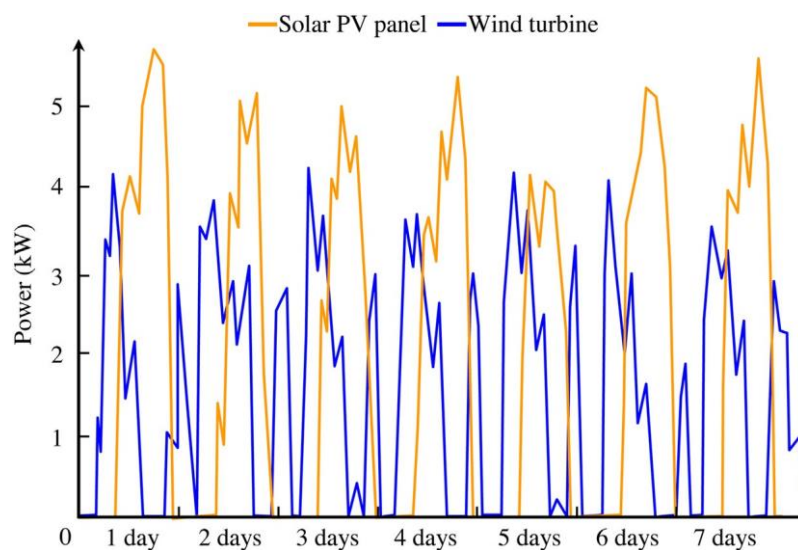


Fig. 4.12. Weekly solar PV panel and wind turbine power generation graph.

Ergy storage power is needed when there is a load demand. A lot of energy is produced from both solar PV panel and wind energy in the morning and noon hours. If this excess amount of energy is more than the amount demanded by the load, the remaining energy can be stored in a battery unit. In the evening the amount of energy produced from solar PV panel and wind energy gradually decreases. These time intervals are the

point where the load demands peaks. In this case, since the power generated from the sources decreases, the energy in the storage unit can be used at noon.

On an annual basis the amount of energy obtained from wind energy reaches its maximum level in autumn and winter. Solar PV panel energy is observed to be at its maximum level in spring and summer months. This seasonal change shows that wind energy is suitable for heating and lighting applications in winter, while solar PV panel energy can be met air conditioning and irrigation needs in summer. In this way, wind and solar PV panel energy together form a complementary system that extends the daily and annual total peak production periods.

The role of the battery in a hybrid renewable energy source is basically to ensure the storage of the excess energy generated and to provide energy to the system when low or no production is produced. If the system is connected to the grid and excess energy is generated in the system, excess energy can be sold to the grid to provide economic incentives. The energy storage unit can help the energy needs during periods of time when housing needs are at their peak by storing energy when low energy is demanded. Thus the user saves money by using the energy storage unit during this high demand for several hours.

The hybrid energy generation system established with solar PV panel and wind energy has a characteristic that complements or supports each other. This complementary of sources enables the energy storage requirement capacity to be reduced. Because when no power is generated from any source, the situations where the user has to take the advantage of the energy storage unit will increase. In addition, as the batteries deep of discharges in the energy storage unit decrease, their service life will increase. The hybrid system is ideal for villages in small isolated areas, because there is no electricity grid in this region. The needed electrical energy can be provided from the renewable energy sources. Remote areas are not the only places where the hybrid renewable energy system can be used effectively. The development of hybrid energy systems for urban environments will create an additional power supply to the grid. In urban areas where lands are costly and people often oppose the construction of new power plants, renewable energy hybrid systems can be created in small-scale housing. Thus a distributed electricity generation system can be

integrated into existing grid infrastructure to meet an increasing load demand. Such a distributed electricity generation system can reduce system losses.

The small-scale hybrid renewable energy system has been classified as the “trend of the future” in a complex urbanization environment. Hybrid renewable energy systems are growing and becoming widespread. Hybrid energy systems are beginning to be seen as the most pragmatic approach to distributed energy generation in a variety of settings. This idea not only minimizes environmental pollution but also benefits to reduce losses in transmission and distribution equipment of existing electrical systems. Hybrid renewable energy systems are a positive trend toward distributed energy generation, helping to reduce business losses on the demand side. Hybrid renewable energy systems are becoming less dependent on the electricity distribution line. Consequently, using hybrid renewable energy systems is an excellent way to advance distributed energy generation. Wind, solar, and current energy sources extend the total peak energy generation times. They complement each other by preserving the battery life in the energy storage system and reducing the total cost of the system. Hybrid renewable energy systems can be adapted to a wide variety of environments, villages, seaside settlements, and urban forests. They are rapidly becoming the preferred system for distributed renewable energy generation.

4.3. Load balancing with hybrid renewable energy sources

Renewable energy sources produce daily energy depending on the periodic characteristics. Due to this irregular output characteristic, the energy generated from these renewable energy sources must be stored. The amount of energy from these sources varies according to the time of the year (seasonal) and weather conditions. Renewable energy sources also can work synchronously with the grid. According to the system status, the excess energy generated is transferred to the grid. In this case the grid actually functions as a buffer or energy storage. Electric load demand in residential applications varies in different time periods during the day. Generally, the demand for electricity usage increases in the evening hours. Fig. 4.13 shows 1-day sample electric power consumption

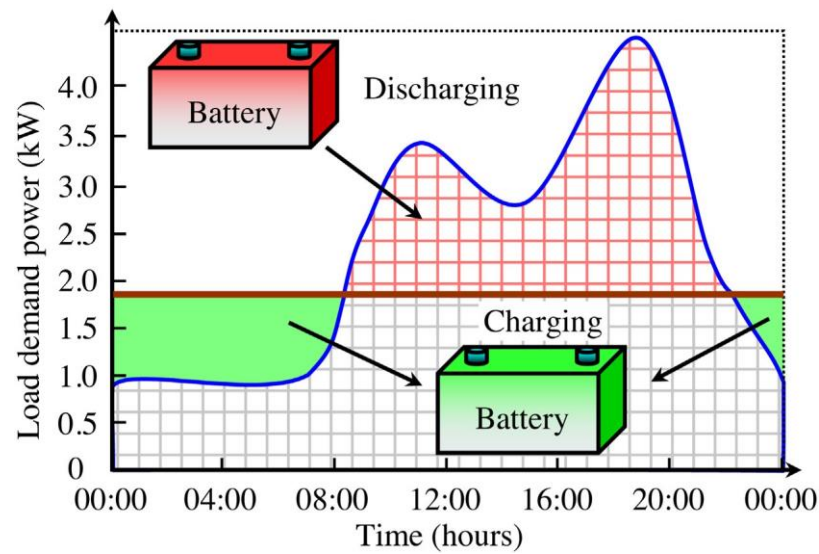


Fig. 4.13. One-day sample electric power consumption graph for residential.

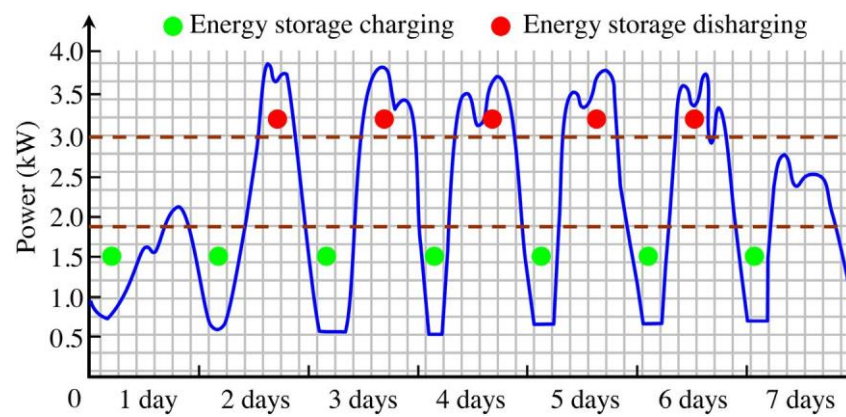


Fig. 4.14. One-week sample electric power consumption graph for residential.

Graph for residential. The devices such as oven, air conditioners, and water heaters demand high energy in residences. Residential electricity needs vary according to the seasons. While heating is used in residences in winter, air conditioners are used in summer.

Electricity use of energy in residences also varies on a weekly basis. While electricity usage for the weekdays is low, it is higher due to the weekend holiday. In order to understand the electricity needs of a residence, the daily energy model must be analyzed correctly. Fig. 4.14 shows 1-week sample electric power consumption graph for residential. Daily and weekly power demand patterns of residences are important for electricity

distribution companies. According to this load model, electricity distribution companies will join an additional power plant to the existing grid. Therefore model estimation of grid-connected loads is very important.

The institution that provides electricity distribution service puts power plants operating with different sources into operation in order to meet the load demands. Thus the load demand on the grid is balanced. The power plants that are commissioned are generally coal-, natural gas-, and oil-based facilities. The electricity distribution company prefers the fastest and cheapest method. These power plants usually take 30–60 minutes to activate. If there is a need for a sudden load in the grid, this is a very long time. A grid with a hybrid structure is required to overcome this problem. This is possible with hybrid renewable energy sources and energy storage units. Sudden loads on the grid can be met quickly with energy storage units. Thus voltage sags and power fluctuations are prevented in the grid. In addition, regional energy storage systems can be activated very quickly. Energy storage systems are charged when the load demand is low. The charging process of the energy storage unit can be done with renewable energy sources. Thus there will be no more energy demand from the grid and the energy storage unit will not be charged with fossil fuels.

Power output characteristics of solar PV panels and wind energy may change over time during the day. This power generation graph may not overlap with the load power graph demanded during the day. If the solar PV panel and wind energy are to be used separately, the sizing should generally be made with high capacity. In this case, system setup cost increases. Power generation interruptions are also high in systems installed separately. Combining solar PV panels and wind energy reduces the fluctuation in output power. Thus system performance and reliability increase and costs decrease. The energy storage sizing to be used in the hybrid system is also reduced. The sizing stage of the hybrid system is more complex as the number of resources increases. Attention should be paid to the parameters in order to produce energy at the optimum level from the hybrid system. These parameters for wind energy are turbine type, turbine rated power, and generator output voltage/current.

Solar PV panels and wind energy are widely used due to their ease of installation and cost effectiveness. The power generation characteristics of these two renewable energy sources are highly variable. Power generation

capacity can be estimated for the location to be installed, thanks to the insolation and wind speed data. This is very important for system sizing. According to these estimated data, the number of solar PV panels and wind turbine generator power will be selected. Most importantly, the capacity of the energy storage unit to be used in the hybrid system will be determined. If the capacity of the energy storage unit is selected high, the energy storage unit will never be charged at full capacity. This will only increase the cost of the system. If the capacity of the energy storage unit is selected low, then the load group in the system cannot be provided energy for the calculated time.

The power generation characteristics of solar PV panels and wind energy are highly variable. Solar energy does not change rapidly. However, wind energy can change hourly. There are variations between the power generation characteristics of solar and wind energy and the time interval of the load demand power. Wind and solar energy sources are complementary. The total power generation graph is tried to be softened with a hybrid system created consisting of solar PV panels and wind turbine. The decision to use both sources in a hybrid system depends entirely on the load and energy storage unit. The aim in the hybrid system is to keep consumption and production equal. It is also to ensure that the energy storage unit is always full. Generally, two power generation sources are expected to complement each other. However, this is not always possible due to natural conditions.

In general, it will not be correct to come to a definite conclusion about the complementarity of these two renewable energy sources, because the source of these two energy generation units is nature. It is possible to make predictions with solar and wind data. Another variable factor is the load profile. The load profile varies greatly over time. Hybrid power generation systems are generally used in areas far from the grid. In the hybrid system the power generation units must be able to meet the total load requirement in the system. The hybrid system must be cost-effective.

CONTROL QUESTIONS

1. What types of hybrid systems are there?
2. For which systems are hybrid renewable energy sources typically selected?
3. In what systems are battery energy storage devices usually used?
4. What is a series hybrid renewable energy system?
5. What is a commutated (switching) hybrid renewable energy system?
6. What is a parallel hybrid renewable energy system?
7. Which criteria are important during the sizing stage of hybrid energy systems?
8. What aspects of the battery group do energy management algorithms control?
9. How are the variable output characteristics of renewable energy sources determined?
10. At what voltage are grid-connected hybrid renewable energy systems typically connected to the grid?
11. What can be used instead of conventional transformers operating at 50–60 Hz?
12. What factors should be considered when calculating the conversion efficiency of wind energy?
13. You skipped number 13 — shall I fill it in if it was missing?
14. At what time of day can photovoltaic panels and wind systems collect the most energy?
15. Under what conditions do fluctuations in output power decrease?

Chapter V

SOLAR HYBRID SYSTEMS AND ENERGY. STORAGE SYSTEMS

5.1. Energy storage systems using in solar hybrid systems

Batteries are chemical circuits that can store the energy resulting from chemical reactions as electrical energy. It consists of unit cells and these cells contain chemical energy that can be converted into electrical energy. One or more of these electrolytic cells are connected in series to form the battery. The grouped cells are added together to form the battery module. The battery pack consists of a combination of battery modules connected in series or parallel combinations.

The four main components of the battery cell are shown in Fig. 5.1.1.:

1. **Positive electrode:** It is an active substance that provides the creation of electrical current. It is an electrode consisting of oxide, sulfite, or any compound that can decrease during discharge. While this electrode battery is discharged, it consumes electrons from the external circuit. Lead oxide and nickel oxide hydroxide are examples of positive electrodes. Electrode materials are solid.
2. **Negative electrode:** It is an active substance that provides the creation of electrical current. It consists of metal or alloy that can be oxidized during discharge. While this electrode battery is discharged, it produces electrons in the external circuit. Lead and cadmium are examples to negative electrodes. Negative electrode materials are also present in the battery cell in a solid state. Negative electrodes of some lithium-ion batteries are made of aluminum to prevent oxidation.
3. **Electrolyte:** It is a solution consisting of charged particles that can transmit and move electrical current. The electrolyte should have high and selective conductivity for the ions involved in the electrode reactions but should not conduct electrons to prevent discharge. Electrolytes can be liquids, gels, or solids, as well as acidic or alkaline depending on the type of battery. Liquid electrolytes are used in conventional batteries such as lead–acid or nickel–cadmium. In lead–acid batteries the electrolyte is in the liquid form of sulfuric acid. More developed batteries such as nickel–metal hydride and lithium ion use electrolytes in the form of gel, paste, or resin. Lithium polymer batteries use solid-state electrolytes.

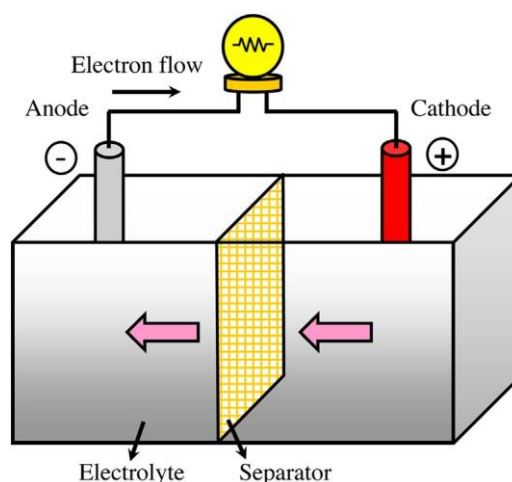


Fig. 5.1. Operating principle of the battery.

4. Separator: It is an electrically insulating layer that physically separates electrodes at different poles. Separators must pass the ions of the electrolytes and have a function that can store the electrolyte and keep it immobile. Separators used today are made of synthetic polymers.

The energy stored in the battery is the difference of chemical energy components between when the battery is charged and discharged. Chemical energy in a cell is converted into electrical energy depending on demand; the unit listed earlier performs this process using the basic elements in the cell. The electrochemically active ones of the positive or negative electrodes are called active substances. The chemical oxidation event takes place in the electrodes due to the electrons that are connected and broken. Electrodes must be conductive in an electronic context, separated by a splitter, and the contacts made on them must be very strong. While the battery is working, chemical reactions in the electrodes cause electrons to flow from one electrode to another. In addition, if the electrons formed during the chemical reaction can flow in an electrical circuit that connects the two electrodes externally, the electron in the cell shows its flow resistance. The connection points between the electrodes and the external electrical circuit are called battery terminals.

Electrochemical batteries can be examined in two classes as primary (nonrechargeable) and secondary (rechargeable) batteries according to their ability to charge electrically. Since the primary-type batteries are nonrechargeable, they cannot be used once again after discharging. Primary cells in the electrolyte containing absorbent and release agent are called dry

cells. Although primary batteries are generally inexpensive, they can be used as a lightweight power pack for portable electronics and electrical devices, in lighting, photographic devices, toys, backup memories, and many other areas. The benefits of primary batteries are as follows: it is easy to reach, simple to use, needs little maintenance if necessary, and can be shaped in connection with the area of use. Other general advantages should have good shelf life, reasonable energy and power densities, reliable and acceptable cost.

At first, the capacity obtained with zinc carbon cells was less than 50 Wh/kg, and now the capacity obtained with lithium cells exceeds 500 Wh/kg. The shelf life of the cells was limited to about 1 year when the batteries were stored at average temperatures during the first commercial years of the batteries. Today, this period varies between 2 and 5 years. With the ability to store even at temperatures as high as 70 °C, the shelf life of the latest lithium batteries is as long as 10 years. Working at low temperature was reduced from 0 °C to -40 °C, -55 °C and the power density was increased. The shelf life of special slow flow batteries using a solid electrolyte exceeds 20 years. Thanks to these advanced features, the usage areas of primary batteries have also expanded. Battery weight and size are also reduced with high energy density. Thus considering the developments in electronic technology, new mobile phone, practical communication, and electronic devices could also be made. The higher power density made it possible to design devices used in computers, mobile phones, military surveillance systems, and other high-power applications. Currently, many primary batteries are used in medical electronic devices, as well as in application areas such as spare memories, as they have a long shelf life.

The use of secondary or rechargeable batteries is quite wide. The most known ones are starter, lighting and ignition systems, and emergency and backup power systems in the automotive industry. Small secondary batteries are also used in portable power supplies such as toys, lighting, photography, radio, and electronic devices such as computers and mobile phones.

In applications used as an energy storage device, it is generally electrically connected and charged by this source. The automotive and aircraft systems, emergency and backup power supplies, and stationary energy storage systems for load balancing are example to these applications. In other applications of secondary batteries, the battery is used like a primary battery,

but it is recharged after use. For example, in terms of economy, portable electronic and electrical devices (thus, the old one can be used instead of a new battery) and some stationary battery applications. In addition to being rechargeable, the secondary batteries can be characterized by high power density, high discharge rate, full discharge profiles, and good performance at low temperature. However, compared to primary batteries, their energy density is generally lower and their charge-holding ability is weaker. Rechargeable batteries have higher energy densities, better charge-holding abilities, and other performance-enhancing properties of this high energy material, using lithium as a negative active material.

5.2. Batteries, their types and working process

Lead–acid (Pb) batteries

Lead–acid batteries have the oldest and most mature technology. It is a low-cost first-action battery created by placing negative lead and positive lead dioxide electrodes into the sulfuric acid electrolyte. Depending on the purpose of use, the number of plates in the electrodes is increased or decreased or their sizes are changed. Parts and general appearance of a typical lead–acid battery are given in Fig. 5.2. The lead–acid battery has a low energy density of 25–35 Wh/kg, although it has passed through many years of development. However, the power density is as high as 150 W/kg. Lead–acid batteries are affected by their low temperatures. There is a serious decrease in both energy and power density at ambient temperatures below 10 °C.

Fig. 5.3 shows the graph of the terminal voltage depending on the battery charge rate of a typical lead–acid battery cell discharged. In a normally accepted

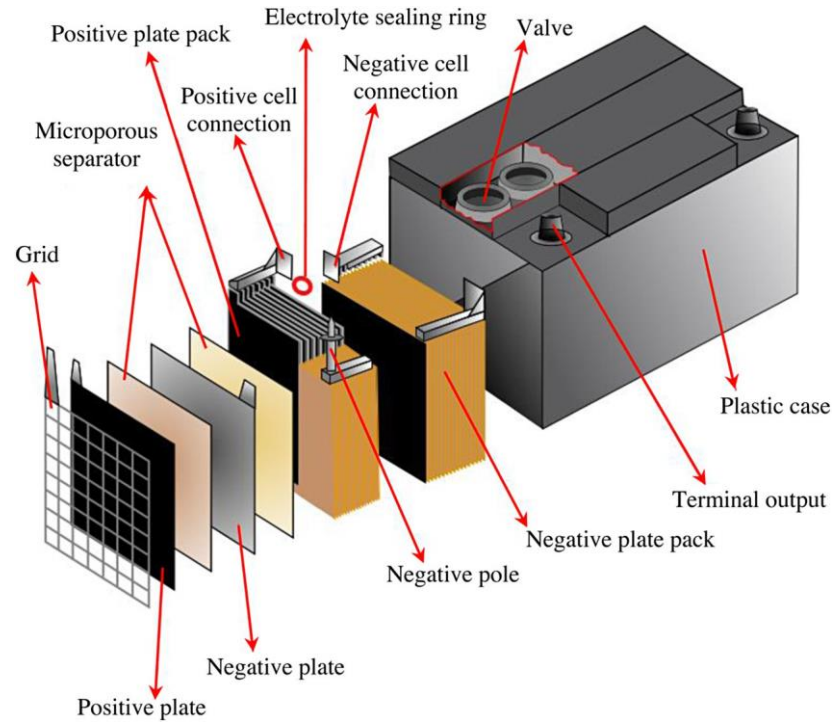


Fig 5.2. Parts and general view of a typical lead–acid battery.

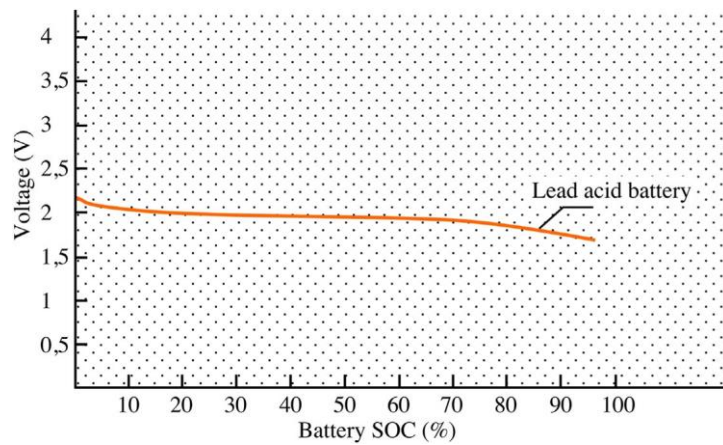


Fig. 5.3. Discharge voltage graph of lead–acid battery cell.

2 V lead–acid cell, the actual voltage is between 2.05 and 2.15 V/cell in relation to the electrolyte density. The voltage value per cell is calculated by taking 2 V.

Nickel–iron (Ni Fe) batteries

It is formed by putting the nickel positive and iron negative electrodes into the potassium hydroxide electrolyte. These batteries are reliable and long-life but costly. These batteries were developed in order to make electric vehicles travel longer. The maximum power density is 100 W/kg and they can maintain their performance down to -20°C . These batteries have a lifetime of up to 2000 deep discharge cycles corresponding to about 6 years. Parts and general appearance of a typical nickel–iron battery are given in Fig. 5.4.

Fig. 5.5 shows the graph of the terminal voltage depending on the battery charge rate of a typical nickel–iron battery cell discharged. The open-circuit voltage of the nickel–iron battery is 1.4 V. The battery nominal voltage is 1.2 V, the maximum charging voltage is usually between 1.7 and 1.8 V. The capacity of the nickel–iron battery depends on the capacity of the positive electrode, so the length and number of each positive plate determines the capacity of the battery.

Nickel–zinc (Ni Zn) batteries

Although the energy density of these rechargeable batteries is 70 Wh/kg and the power density is 150 W/kg, it is disadvantageous to have a lifetime of 300. The use of these batteries has not become widespread, since dendrites on the zinc plate shorten the life of the battery during charging. The battery has a wide

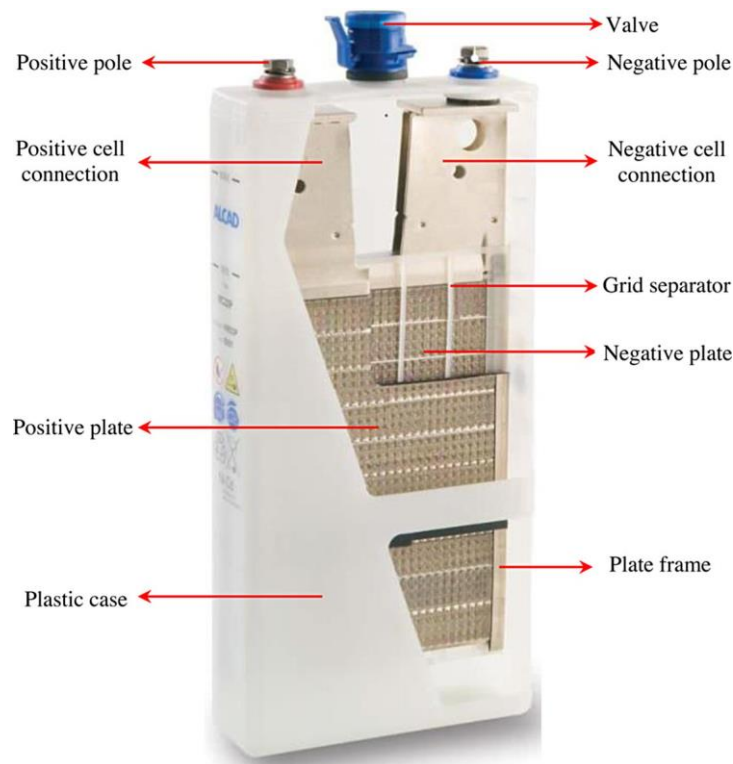


Fig. 5.4. Parts and general appearance of a typical nickel–iron battery.

Operating temperature tolerance ($-39\text{ }^{\circ}\text{C}$ to $+81\text{ }^{\circ}\text{C}$). After 30 days of use, there is a 60 % reduction in charge. A single nickel–zinc cell can be combined with various designs into multiple cells in traditional ways to be transformed into a monoblock-type battery. Parts and general appearance of a typical nickel–zinc battery are given in Fig. 5.6.

In practice, the working voltages of nickel–zinc batteries under load are between 1.55 and 1.65 V and approximate energy densities are 70 Wh/kg depending on special designs. A single nickel–zinc cell provides 1.65 V. Nickel–zinc batteries produced in monoblock-type are usually turned into a 12-V typical battery, containing seven or eight cell modules. Fig. 5.7 shows the graph of the terminal voltage depending on the battery charge rate of a typical nickel–zinc battery cell discharged.

Nickel–cadmium (Ni Cd) batteries

It is formed by placing the sintered positive nickel electrode and negative cadmium electrode in the potassium hydroxide aqueous solution. In recent years, it

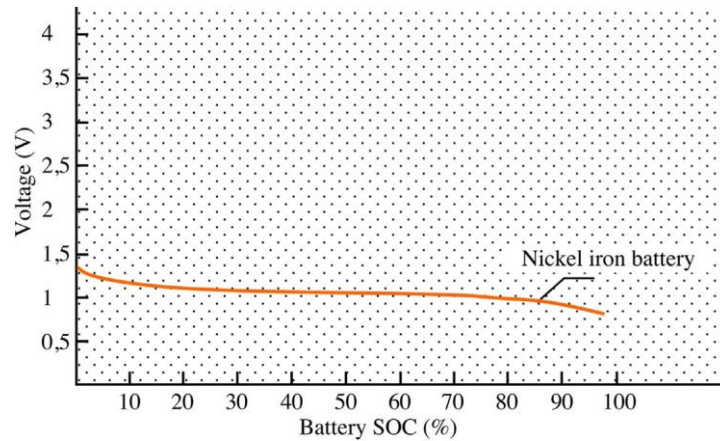


Fig. 5.5, Discharge voltage graph of nickel–iron battery cel

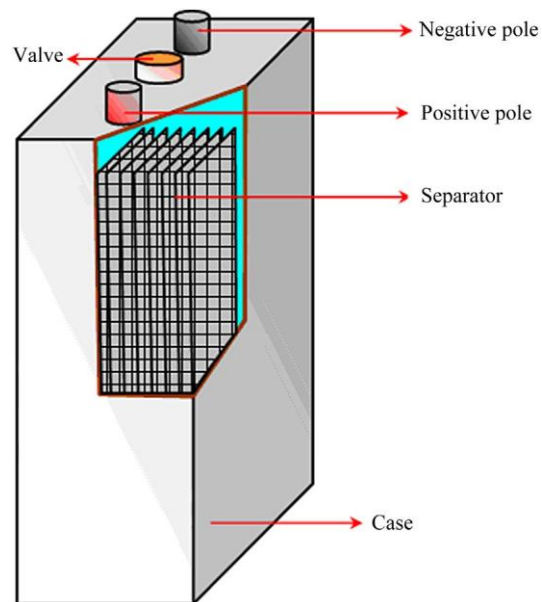


Fig. 5.6. Parts and general appearance of a typical nickel–zinc battery.

Is considered as a battery that provides good balance in terms of specific energy, specific power, cycle life, and reliability. Because cadmium is toxic and environmentally hazardous, recovery of nickel–cadmium batteries is very important and complex. Their use has been discontinued due to the damage to the environment. These batteries have a high charge/discharge rate and the number of deep discharge cycles is around 2000. The internal resistance of nickel–cadmium

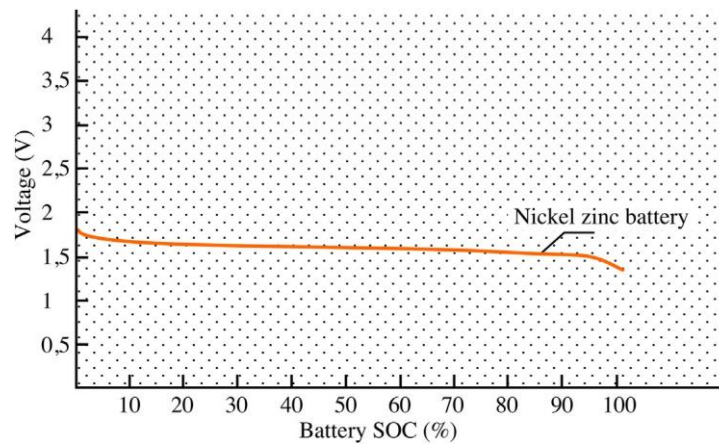


Fig 5.7. Discharge voltage graph of nickel–zinc battery cell.

Batteries is generally very low. A typical direct current (DC) resistance value is 0.4, 1, and 4 m Ω , respectively, high-, medium-, and low charge rate for the 100 Ah charge value. The decrease in temperature and battery charge will cause an increase in internal resistance. Depending on the working conditions and battery design, the total working life varies between 8 and 25 years. Parts and general appearance of a typical nickel–cadmium battery are given in Fig. 5.8.

The energy density of a typical nickel–cadmium cell is 20 Wh/kg and 40 Wh/L. The nominal voltage of the nickel–cadmium battery cell is 1.2 V. Although the battery discharge rate and battery temperature are an important variable for chemical batteries, these parameters have little effect in nickel–cadmium batteries compared to lead–acid batteries. Therefore nickel–cadmium batteries can be used at high discharge rates without losing their nominal capacity. Nickel–cadmium batteries also have a wide range of operating temperatures. A standard nickel–cadmium battery cell can operate between -20°C and $+50^{\circ}\text{C}$. Fig. 5.9 shows the graph of the terminal voltage depending on the battery charge rate of a typical nickel–cadmium battery cell discharged.

Nickel–metal hydride (NiMH) batteries

Nickel–metal hydride batteries have recently been used in many electric car applications since they do not have oxide properties and have better performance. Nickel–metal hydride batteries store more energy than nickel–cadmium batteries. The negative electrode, which is a metal hydride mixture,

consists of the potassium hydroxide electrolyte and the positive electrode, the active material of which is nickel hydroxide. With an energy density of more than 70 Wh/kg and a power density of more than 200 W/kg, these batteries are about five times more expensive than lead–acid batteries. The battery has over 600 full charge/discharge cycles in the case of 80 % deep discharge and it is about 35 minutes

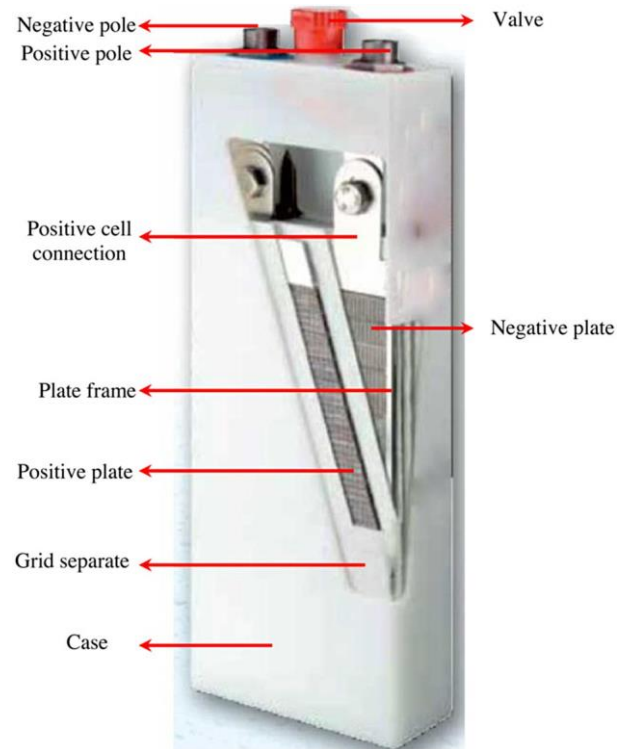


Fig. 5.8. Parts and general appearance of a typical nickel–cadmium battery.

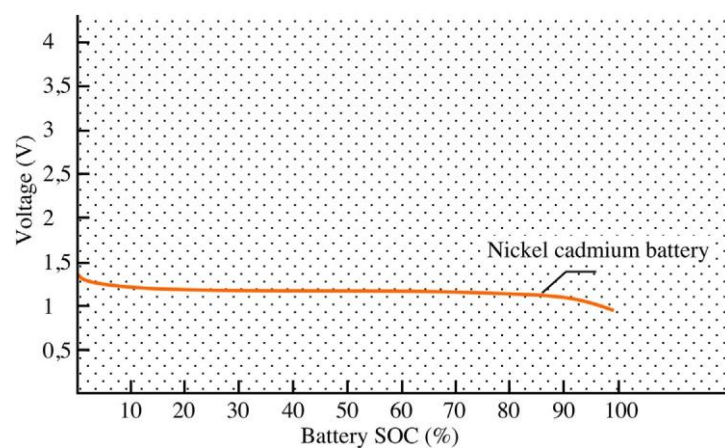


Fig. 5.9. Discharge voltage graph of nickel–cadmium battery cell.

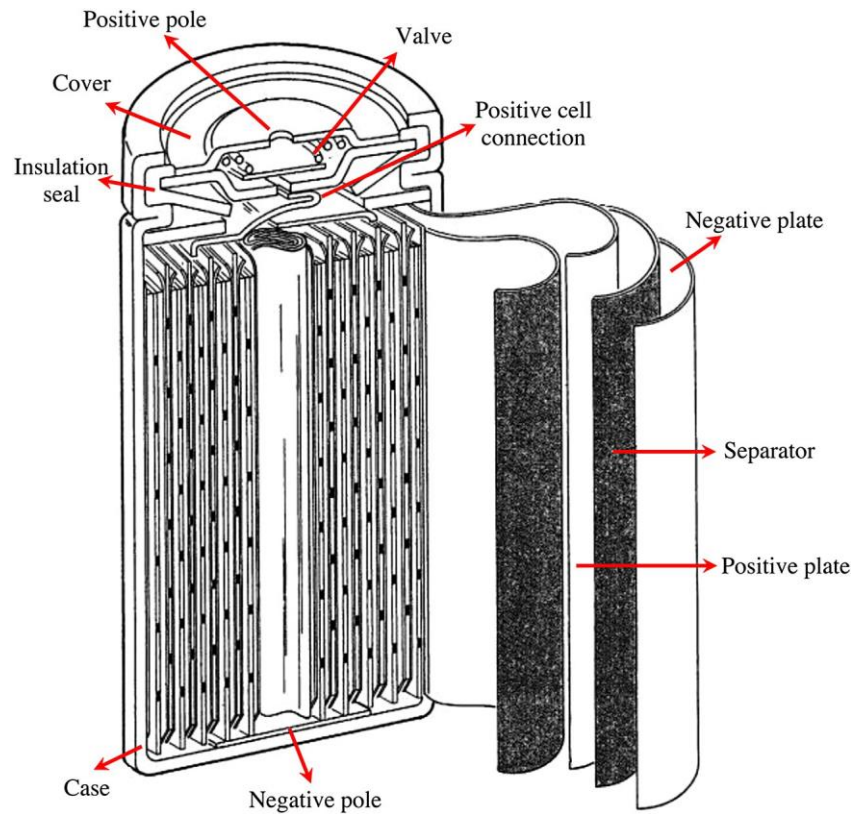


Fig. 5.10. Parts and general appearance of a typical nickel–metal hydride battery.

To quickly recharge 80 %. Sealed nickel–metal hydride cells and batteries are produced in cylindrical, button, and prismatic ways. Parts and general view of a typical nickel–metal hydride battery are given in Fig. 5.10.

The nominal voltage of a nickel–metal hydride cell is 1.2 V, and the open circuit voltage is between 1.25 and 1.35 V. Battery discharge cutoff voltage or final voltage is 1 V. The operating temperature of a standard nickel–metal hydride battery cell is between 0 °C and +40 °C. Operation of nickel–metal hydride batteries at high temperatures affects the performance characteristics of the batteries. The performance of the batteries at high temperatures is further reduced compared to the low discharge temperature due to the increased internal resistance. Similarly, temperature change effects are more pronounced at high discharge rates. Fig. 5.11 shows the graph of the terminal voltage depending on the battery charge rate of a typical nickel–cadmium battery cell discharged. At

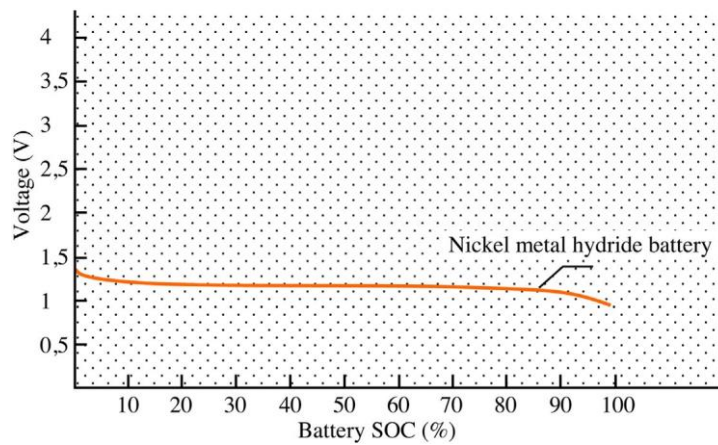


Fig. 5.11. Discharge voltage graph of nickel–metal hydride battery cell.

Low temperatures, especially when the discharge rate increases, the capacity of the battery decreases.

Sodium–sulfur (NaS) batteries

The sodium–sulfur battery is formed by combining the liquid states of the negative sodium and positive sulfur electrodes. Both electrode components are in a liquid state. It has been developed to provide the energy and power density required for electric vehicles. The optimum operating temperature is 350 °C and stops operating below 200 °C. The reaction slows down as the sodium electrolyte freezes below this temperature. Freezing of sodium slows down the reaction and damages the battery due to mechanical stresses. The battery heater is needed to determine the operating temperature. It is necessary to be well insulated for easy maintenance and its temperature does not pose a danger. The charging time of the sodium–sulfur battery is 4–5 hours. Their lifespan is longer than the life of the lead–acid battery. The substances used in the structure of this battery are harmful to health. Sodium–sulfur batteries provide high energy density of 110 Wh/kg and power density of 150 W/kg. Parts and general appearance of a typical sodium–sulfur battery are given in Fig. 5.12.

Sodium–nickel chloride (Na Ni Cl) batteries

Nickel chloride is positive electrode and sodium is negative electrode. Instead of sodium salt electrolyte, sodium chloride electrode is located. This electrode has a lower freezing point and it is around 160 °C. This type of

battery operates at

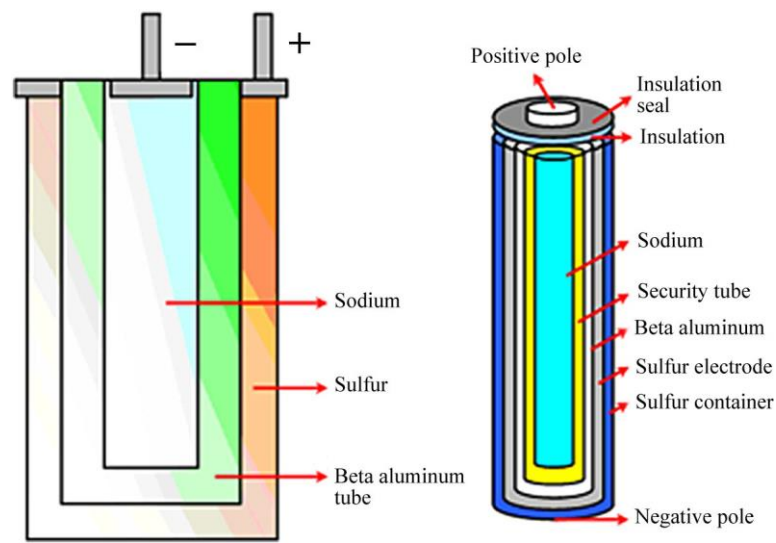


Fig. 5.12. Parts and general appearance of sodium–sulfur battery.

Somewhat low temperatures (300 °C) compared to the sodium sulfide battery and has similar energy (100 Wh/kg) and maximum power density (150 W/kg).

Aluminum–air (Al–air) and zinc–air (Zn–air) batteries

Alkaline water–based electrolyte such as thin gas permeable cathode and potassium hydroxide are used in all air–metal batteries. Zinc and aluminum are the most commonly used metal electrodes in such applications. The maximum energy density of the aluminum–air battery is 220 Wh/kg, and the zinc–air battery is 200 Wh/kg. However, the rate of exchange between air and electrolyte determines the power density and this speed is very low.

5.3. Lithium-ion (Li-ion) batteries

Negative “hosts” such as graphite or tin oxide are used as negative electrodes in lithium-ion cells. During discharge, lithium ions change from negative “host” to organic “electrode” to manganese, cobalt or nickel oxide positive “host.” The reverse process takes place during charging, and lithium ions act like a pendulum between the cathode and the anode. It has an energy density of approximately 150 Wh/kg and a deep discharge cycle of 1000 cycles. These batteries can be recharged in less than 1 hour to the 80 % charge

state. Due to these features, lithium has become one of the most preferred elements of rechargeable battery technologies. Lithium metal oxide and lithium metal phosphate-based “cathode” (positive electrode) materials are especially preferred in mobile

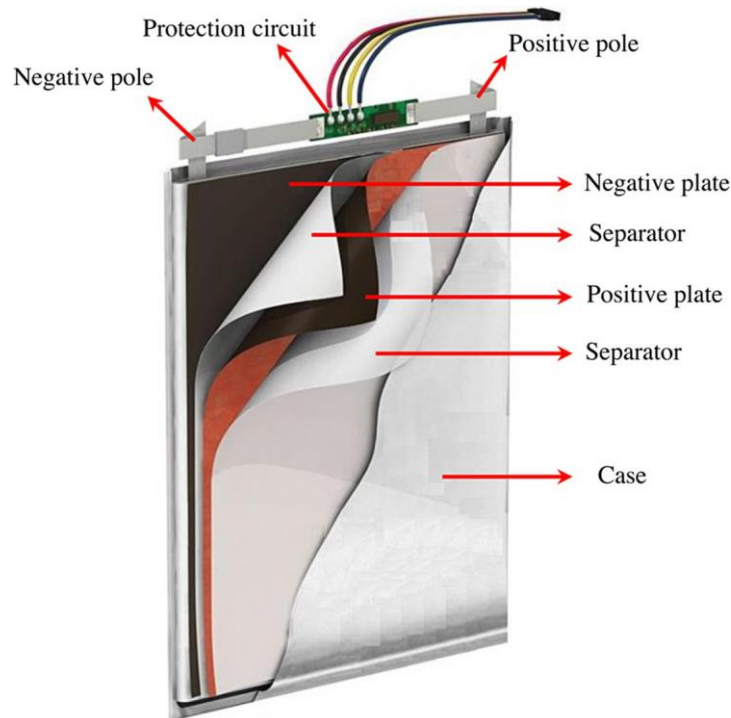


Fig. 5.13. Parts and general appearance of lithium-ion battery.

Equipment and electric vehicles. They can provide very high energy storage density as a rechargeable battery. Parts and general appearance of a typical lithium-ion battery are given in Fig. 5.13.

The operating temperature of lithium-ion batteries during charging is between $-20\text{ }^{\circ}\text{C}$ and $+60\text{ }^{\circ}\text{C}$, and when discharging the temperature is between $-40\text{ }^{\circ}\text{C}$ and $+65\text{ }^{\circ}\text{C}$. The cell voltage of a typical lithium-ion battery is 2.5–4.2 V, and this voltage value is approximately three times the nickel–cadmium and nickel–metal hydride battery cell voltage. Fig. 5.14 shows the graph of the terminal voltage depending on the battery charge rate of a typical lithium-ion battery cell discharged.

Lithium-ion batteries, which are in the development phase, vary according to the chemicals used. For example, when lithium–manganese oxide ($\text{Li Mn}_2 \text{O}_4$) is used instead of lithium–cobalt oxide (Li Co O_2), the risk of explosion by cobalt is eliminated. However, the performance decreases

dramatically when these types of batteries exceed 50 °C. On the other hand, when using manganese, the energy density decreases by 20 %. However, manganese is a much safer and environment-friendly element than cobalt. However, cobalt-based lithium-ion batteries are preferred due to their energy density. In the use of nickel oxide

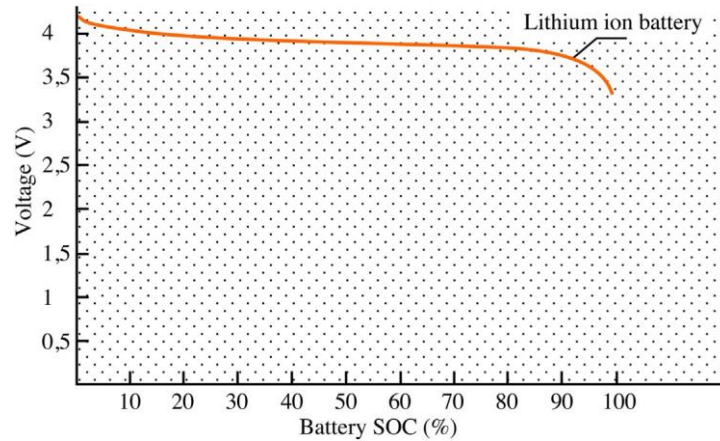


Fig.5.14. Discharge voltage graph of lithium-ion battery cell.

Metal (LiNiO_2), the energy density of the lithium-ion battery is increased by 30 % compared to cobalt. However, because of the exothermic reaction that produces much higher heat, cooling problems occur in nickel-based batteries. In industry, three-metal $\text{Li}(\text{Ni Co Mn})\text{O}_2$ type is also tried and some cheap and safe parameters can be obtained. Some of the commercially produced lithium-ion battery types are as follows:

- lithium–cobalt oxide (Li Co O_2),
- lithium–manganese oxide ($\text{Li Mn}_2 \text{O}_4$),
- lithium–nickel oxide (Li Ni O_2),
- lithium–iron phosphate (Li Fe PO_4),
- lithium–titanate ($\text{Li}_2 \text{Ti O}_3$),
- lithium–titanate spinel ($\text{Li}_4 \text{Ti}_5 \text{O}_{12}$),
- lithium sulfur ($\text{Li}_2 \text{S}$),
- lithium–nickel cobalt oxide ($\text{Li}(\text{Ni Co})\text{O}_2$),
- lithium–nickel cobalt magnesium oxide ($\text{Li}(\text{Ni Co Mn})\text{O}_2$), and
- lithium–nickel cobalt aluminum oxide ($\text{Li}(\text{Ni Co Al})\text{O}_2$).

Lithium-ion polymer batteries

Unlike lithium-ion batteries, lithium salt is kept in the solid polymer mixture instead of organic solution. This design has many advantages, such as the solid polymer being nonflammable. Lithium-ion batteries are in prismatic or cylindrical metal sheaths and have a burning feature if exposed to sunlight. However, different shape designs can be realized by using flexible polymers in lithium-ion polymer batteries. In addition, one of the differences between commercial lithium-ion polymer and lithium-ion cells is that in lithium-ion cells, the metal



Fig, 5.15. Parts and general appearance of lithium-ion polymer battery.

Sheath must press the electrodes and separators, whereas lithium-ion polymer batteries do not. As they do not need metal sheaths, they can be shaped lightly and easily. Thus 20 % more cells of equal weight can be placed than lithium-ion cells and even three times more energy density than nickel–cadmium or nickel–metal hydride batteries. The polymer cell voltage ranges from 2.7 (empty) to 4.23 V (fully charged) and must be protected against charging more than 4235 V for counter-connected cells. Excessive charging can cause an explosion or burns. Again, for the cell connected in series, the load should be removed when the discharge voltage drops below 3 V,

otherwise the battery will not accept a longer charge. Parts and general appearance of a typical lithium-ion polymer battery are given in Fig. 5.15.

Lithium–iron phosphate (LiFePO₄) batteries

The cathode material is made of lithium metal phosphate material instead of lithium metal oxide, which is another type of lithium-ion batteries and briefly called lithium iron or lithium ferrite in the market. As metal, iron, cobalt, manganese, or titanium are used. Lithium–iron phosphate battery technology was scientifically reported by Akshaya Padhi of the University of Texas in 1996. Lithium–iron phosphate batteries, one of the most suitable in terms of performance and production, started mass production commercially. Lithium–iron phosphate batteries have a high energy density of 220 Wh/L and 100–140 Wh/kg, and also the battery charge efficiency is greater than 90 %. The cycle life is approximately 2000 at a deep discharge rate of 80 %. The operating temperatures of lithium–iron phosphate batteries that perform well at high operating temperatures are between $-20\text{ }^{\circ}\text{C}$ and $+70\text{ }^{\circ}\text{C}$.

Comparison of lithium-ion batteries

The comparison of terminal voltage and energy density of lithium–cobalt oxide (Li Co O_2), lithium–nickel cobalt aluminum oxide ($\text{Li}(\text{Ni Co Al})\text{O}_2$), lithium–nickel cobalt magnesium oxide ($\text{Li}(\text{Ni Co Al})\text{O}_2$), lithium–manganese oxide ($\text{Li Mn}_2 \text{O}_4$), and lithium–iron phosphate (Li FeP O_4) battery cells, which are lithium-ion battery types, with numerical data is given in Table 5.1. Depending on the different chemical materials used in lithium-ion batteries, terminal voltages and energy densities of the batteries vary.

Although the use of different materials in lithium-ion batteries changes gravimetric or volumetric energy density in some battery types, it shows positive or negative effects on many issues such as cost and safety battery life. Comparison of lithium–cobalt oxide (LiCoO_2), lithium–manganese oxide ($\text{Li Mn}_2 \text{O}_4$), lithium–iron phosphate (Li Fe PO_4), lithium–nickel cobalt magnesium oxide ($\text{Li}(\text{Ni Co Mn})\text{O}_2$), lithium–nickel cobalt aluminum oxide ($\text{Li}(\text{Ni Co Al})\text{O}_2$), and lithium–titanate spinel ($\text{Li}_{14} \text{Ti}_{15} \text{O}_{12}$) batteries, which are lithium-ion battery types, by scaling specific energy, specific power, safety, performance, life, and cost issues can be seen in Fig. 5.16. While different chemical

materials used in lithium-ion batteries increase their specific energy in one type, performance effect is seen in another. It can be seen from the scaled comparison that the studies required to get the most out of these six subjects are still continuing.

Table 5.1

Voltage and energy densities of lithium-ion battery types.

Battery types	Voltage (V)	Energy densities	
		Gravimetric (Wh/kg)	Volumetric (Wh/kg)
$\text{Li C}_0 \text{O}_2$	3.7	195	560
$\text{Li (N}_i \text{C}_0 \text{Al)} \text{O}_2$	3.6	220	600
$\text{Li (N}_i \text{C}_0 \text{M}_n) \text{O}_2$	3.6	205	580
$\text{Li M}_{n2} \text{O}_4$	3.9	150	420
Li Fe PO_4	3.2	90–130	333

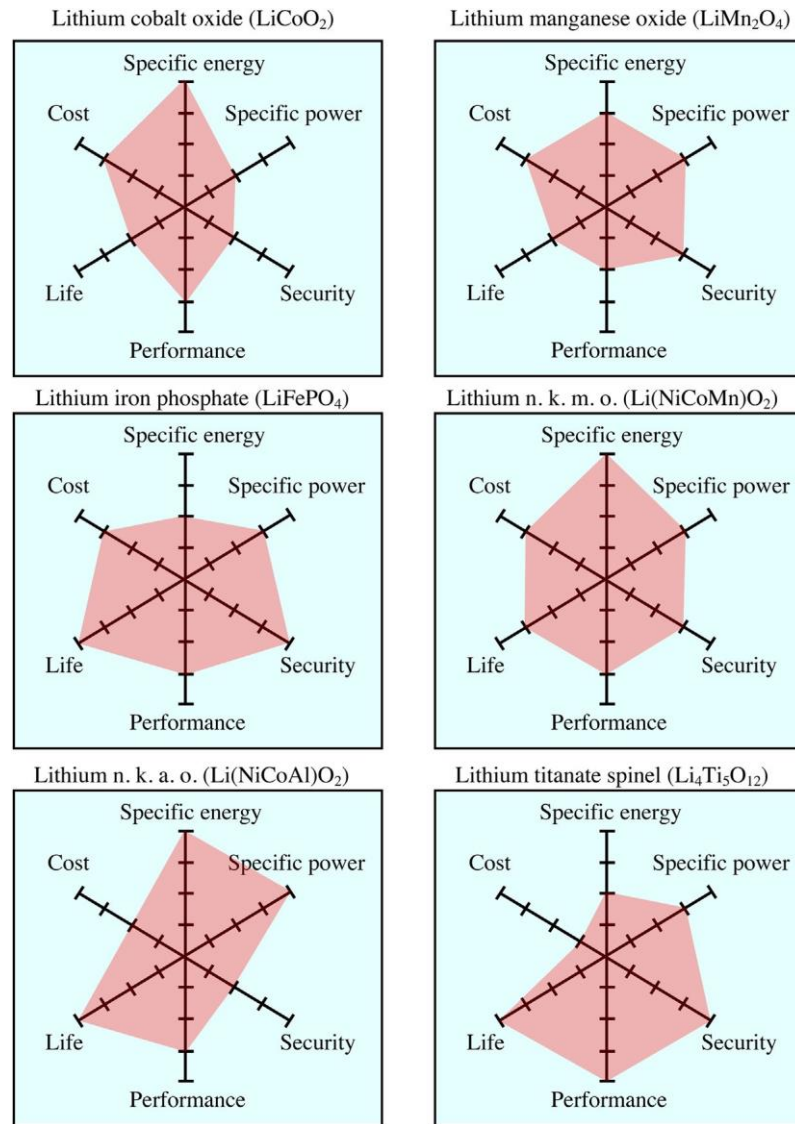


Fig.5.16. Scaling comparisons of lithium-ion batteries.

Lithium-ion batteries offer the optimum solution in terms of weight and volume for portable devices and electric vehicles. With today's technology the highest voltage per unit cell and the highest energy density per unit mass (Wh/kg), in other words, the highest specific energy can be provided by lithium-ion batteries. They are also efficient because they are not affected by the memory effect problem, and interrupting the charging/discharging process does not constitute a negative situation.

However, since lithium is a substance that can react very quickly, lithium-containing batteries have a risk of burning and explosion. New electrode designs are being developed and materials used for electrolyte are constantly being improved, and safer batteries are being introduced day by day. During the charging process, constant voltage method should be used and after the

battery voltage reaches a certain value, this voltage should be kept constant and the charging current should be reduced. Otherwise, an overcharged battery may explode. Discharge should be stopped when a certain cutting voltage is reached during the discharge process. Damage occurs in batteries that are tried to be discharged below this cutting voltage.

Comparison of rechargeable battery types

Comparison of rechargeable batteries with different chemical structure in terms of energy density is given in Fig. 5.17. The developed battery technology has an increasingly less volume and less weight feature. In a comparison in Wh, lithium-ion technology appears to be in top condition compared to other batteries.

In Table 5.2, energy and power density, efficiency, self-discharge, charge/discharge cycle, and nominal voltage comparison of rechargeable batteries are given. As a charge/discharge cycle, lithium-ion batteries are quite high compared to lead–acid batteries and are approximately 1200 cycles. When examined in terms of efficiency, lithium-ion batteries are the most efficient battery with a rate of 99 %. In addition, when examined in terms of power and energy density, lithium-ion battery technology is at the forefront with very high values. When examined in terms of nominal voltage, lithium-ion battery technology appears to be the highest battery terminal with 4 V. The discharge voltage graphs of the rechargeable battery cells are given in detail in Fig. 5.18 depending on the battery charge status. It is a nickel–iron battery with the lowest.

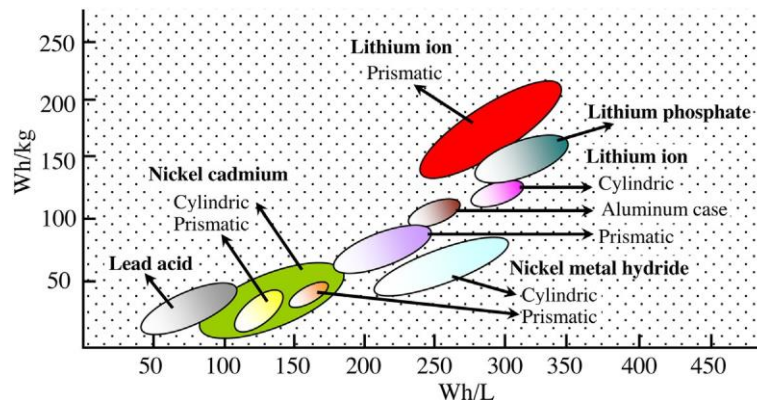


Fig. 5.17. Comparison of secondary batteries in terms of energy density

Table 5.2.

Performance characteristics of rechargeable batteries.

Batteries	Energy density (Wh/kg)	Power density (Wh/kg)	Efficiency (%)	Self-discharge (%/month)	Charge/discharge cycle	Nominal voltage (V)
Lead–acid	30–40	180	70–92	3–4	500–800	2.0
Nickel–cadmium	40–60	150	70–90	20	1500	1.2
Nickel–metal hydride	30–80	250–1000	66	20	1000	1.2
Nickel–iron	50	100	65	20–40	2000–4000	1.2
Nickel–zinc	60	900	70	<20	100–500	1.65
Zinc–silver oxide	130	>1000	70–90	5	50–100	1.5
Cadmium–silver oxide	70	<1000	90	5	300–800	1.2
Nickel–hydrogen	75	<1000	60	High	20,000	1.3
Lithium-ion	160	1800	99	5–10	1200	4.0
Lithium-polymer	130–200	>3000	99	5–10	500–1000	3.7

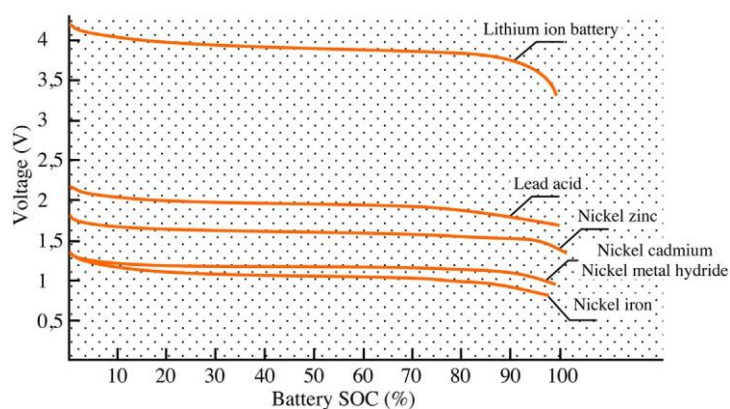


Fig. 5.18. Discharge voltage graphs of rechargeable battery cells.

Operating voltage below 1.2 V. Nickel–cadmium and nickel–metal hydride coil types draw approximately the same discharge curve as 1.2 V.

Ultra capacitor.

Capacitors are devices that store energy by decomposition of positive and negative electrostatic charges. Capacitors consist of two conductive plates and insulators called dielectrics that separate them. The dielectric material prevents arcing between the two plates, helping to charge more. Classical capacitors have very high power densities (approximately 10^{12} W/m^3). However, their energy intensity is very low (approximately 5 Wh/m^3). Classical capacitors are commonly referred to as electrolytic capacitors. Ultra capacitors are the developed ones of classical capacitors. The power densities of these capacitors are 10^6 W/m^3 and the energy densities are 10^4 Wh/m^3 . Energy intensities are low but discharge times are fast and cycle life is higher. However, capacitors actually have size problems. There is a linear connection between the capacitors' capacitance and the dielectric material. Therefore when large capacity is required, the dielectric material must also be large. Thanks to the ultra capacitors, very large capacity values provided high energy storage with very small capacitors. Fig. 5.19 shows the parts and general appearance of a typical ultra capacitor.

Ultra capacitors are energy storage systems that act basically like capacitors but separate from capacitors in terms of high energy and power density. As a result, these new types of energy storage systems known as electrochemical capacitors or ultra capacitors are a very intensive research topic. The use of ultra capacitors as an alternative for applications that require high energy and power density where batteries and capacitors cannot be used increases their importance. Since there is no phase change in the electrochemical process in the ultra capacitors, such capacitors can be filled and discharged more than 100,000 times.

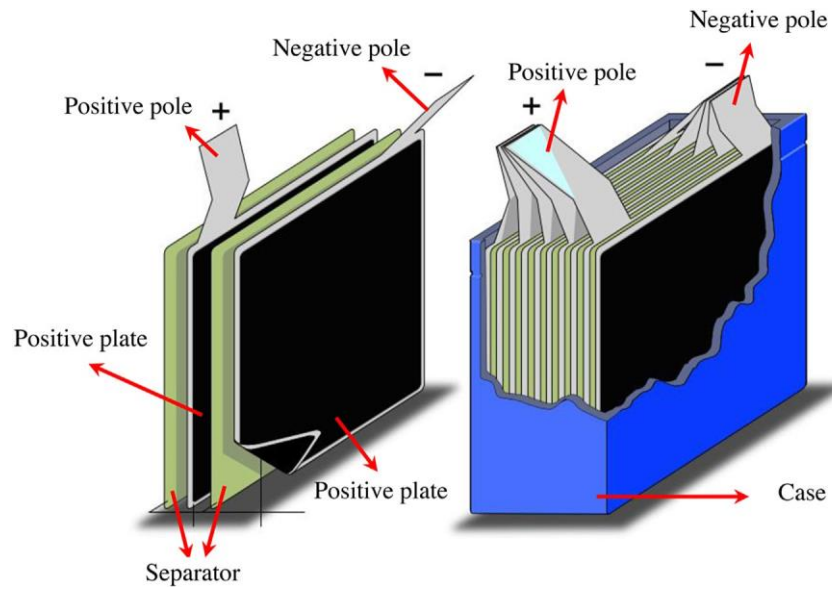


Fig. 5.19. Ultra capacitor parts and general appearance.

Fig. 5.20 shows the typical Ragone graph that gives energy intensity versus power intensity. The Ragone graph is a chart used to compare the power densities of various energy storage systems against the energy densities. In the Ragone graphic the energy density (vertical axis) defines how much energy can

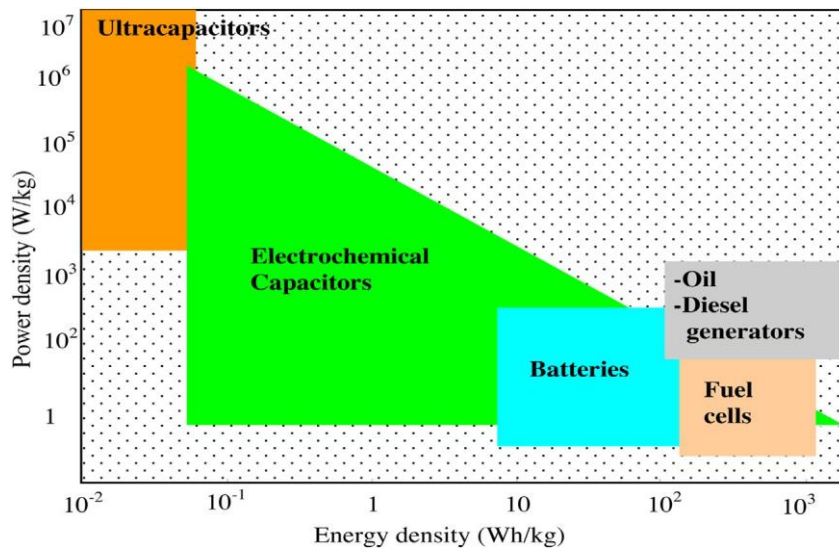


Fig 5.20. Ragone graphic for different types of energy storage systems.

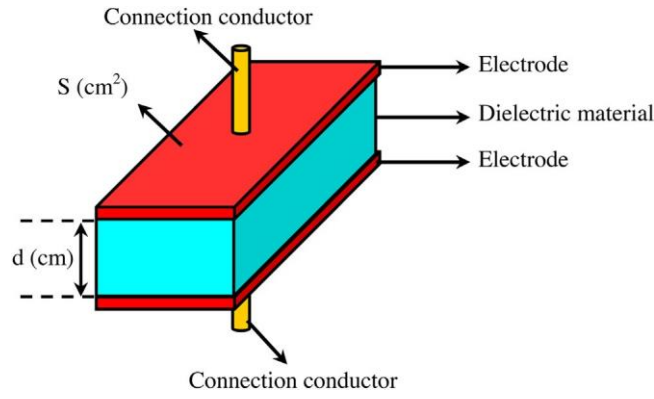


Fig. 5.21. Structure of conventional electrostatic capacitor.

Be stored, and the power density (vertical axis) defines how long the stored energy can be transferred. According to this graph, ultra capacitors have high power density and low energy density, while fuel cells and batteries have high energy but limited power density. The slow power transfer of lithium-ion batteries and advanced secondary batteries has increased the need for systems with higher energy and power density in many new applications. In the power density and energy density scale, ultra capacitors fill the gap between the batteries and electrolytic capacitors. Since the working principle of electrochemical capacitors contains similarities with traditional capacitors, the study of the working mechanism of traditional capacitors is an important step to illuminate the working mechanism of ultra capacitors. Conventional capacitors are devices created by placing a dielectric material between two conductive materials, as shown in Fig. 5.21. Load accumulation on the conductive sheet is achieved by the potential application to the conductive sheet, and the sheets remain loaded when the potential applied to the sheets is removed. The V is capacitor voltage, and the Q is load on the plates; Q/V ratio is called capacitance (C). In the following equation the capacitance formula is given:

$$C = \frac{Q}{V} \quad (5.1)$$

Capacitance is usually denoted by C and its unit is Farad (F). Since F is very large, it is usually measured in microfarad (μF) or picofarad (pF). The structure of conventional electrochemical capacitor is shown in Fig. 5.22.

Ultra capacitors must have high ionic electrolyte conductivity, high ionic separator conductivity, high electronic separator resistance, high electrode

electronic conductivity, high electrode surface area, low separator, and electrode thickness. The internal structure of a typical ultra capacitor is given in Fig. 5.23.

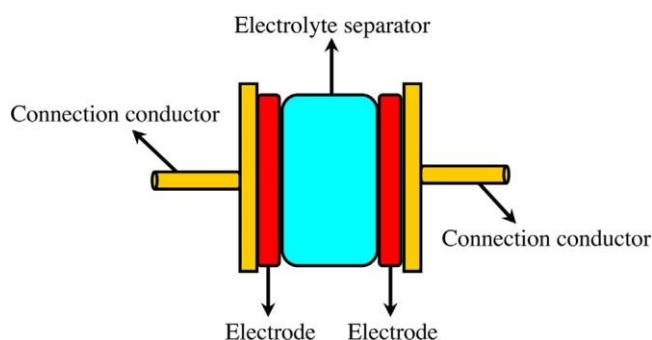


Fig 5.22. Structure of conventional electrochemical capacitor

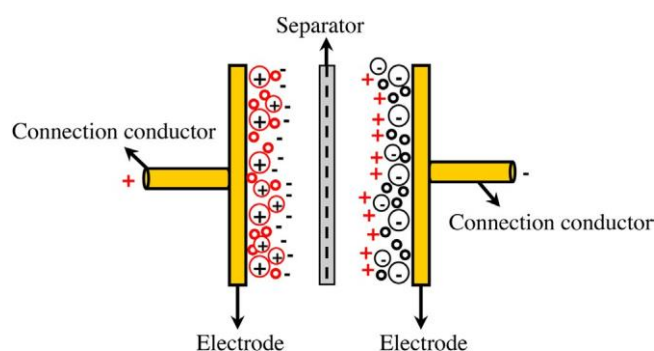


Fig. 5.23. Internal structure of traditional ultra capacitor.

Ultra capacitors consist of the following elements:

Electrodes: The reason for the high capacitances obtained in ultra capacitors is the electrodes with high surface area that provide good contact between the electrode and the electrolyte. Electrodes must have a high surface area and be electrochemically inert (inactive substance). For this purpose, highly reactive metal oxides, carbon, graphite, conductive polymers, and their composites can be used. Capacitance can reach 250 F/g in ultra capacitors using carbon.

Electrolyte: Electrolytes used in ultra capacitors can be in solid, organic, or aqueous form. The electrolyte used must have high conductivity and electrochemical stability that allows the capacitor to operate at the highest possible voltage.

Separator: Different separators can be used depending on the type of electrolyte used. While polymer or paper separators are more suitable for organic electrolytes, glass fiber or ceramic separators are more suitable for aqueous electrolytes.

Although the working principle of

electrochemical capacitors is similar to the working principle of conventional capacitors, the charge accumulation Fig. 5.22 Structure of conventional electrochemical capacitor. Fig. 5.23. Internal structure of traditional ultra capacitor of electrochemical capacitors does not occur on conductive sheets separated by an insulator, unlike conventional capacitors. Conceptual structure of electrochemical capacitors is shown in Fig. 5.23; the charge accumulation on the electrodes depends on the change in the intersection between the electrolytic solution and the electrode surface. At this point, as with electrical double-layer capacitors, charge accumulation occurs in the called electrical double layer (electrode–electrolyte solution interface). The ionic separation distance depends on the size of the ions and the concentration of the electrolyte solution. Ultra capacitors have higher specific capacitance values than electrostatic capacitors because they are based on electrochemical double layer basis.

Usage areas and applications of ultra capacitors

The first examples of ultra capacitors were patented by General Electric in 1957 but were not offered for use. The first example was patented in 1978; it had 5 m³ dimensions, 5 V voltage, and higher capacitance than 1 F. This capacitor is used to prevent data loss in computers. Although ultra capacitors did not show much improvement until the early 1990s, designers have focused on the cell design of capacitors. They also investigated the functions of working principles related to direct and alternating current.

In the early 1990 s a company in Moscow developed a structure called asymmetrical design in capacitors and used it as the power supplier of an all-electric bus. The charging time was ahead of its time with a usage area limited to half an hour and 15 km in distance. The ultra capacitors used could store 8 kWh of energy. A similar solution was introduced in Shanghai in 2010. These buses are constantly charging between the stops and the charging time is only 20 seconds. Ultra capacitors are used for the operation of camera flashes that require instant energy release. The ultra capacitor connected to the flash is first charged by the battery, then it is activated at the time of shooting and the stored high energy is transmitted to the flash at once. Thus high light is obtained instantaneously. Increasing carbon dioxide emissions in the world have pushed

many car manufacturers to develop hybrid or electric vehicles. Volvo, one of the car manufacturers, used ultra capacitor as an energy-storage element in electric vehicle application. The fact that these carbon fiber and polymer-based ultra capacitors can also be used as body elements has eliminated the need for a battery compartment that causes additional weight.

Rory Handel and Maxx Bricklin, who set off for a wind-powered car design, designed the RORMAx Formula AE, which uses alternative energy, the Formula vehicle. The concept car is intended to cause less harm to nature by using technologies such as ultra capacitor, solar panels, and airflow converter. The vehicle, which is activated with the energy provided by the ultra capacitors, can then increase its charge up to 25 % by using the wind passing over it. It is thought that this car, which is expected to complete 0–100 km acceleration under 4 seconds with the calculations made on paper, can reach 230 km final speed and can go 300 km with 90-minute charge. The prototype was completed in ugust 2009.

Electric buses in Shanghai can operate without the need for an electric line, thanks to ultra capacitors. Thanks to the fast charging feature of the ultra capacitors, they can only be transported by charging at the stops. Ultra capacitors have created a solution, for electronic devices, memory of which can be erased in the case of power cuts. Examples of such devices are digital wrist watches, some computer parts, and mobile phones. The ultra capacitors on digital watches and mobile phones are activated when the battery is exhausted, and it prevents the loss of watches and some important information, in particular. When the batteries of some mobile phones are removed and inserted back for a few seconds, it reminds the clock at the opening with the help of ultra capacitors. is used for the purpose of creating artificial lightning in the laboratory environment by utilizing the ability of ultra capacitors to discharge suddenly. An artificial lightning is created by bringing together a large number of ultra capacitor blocks. The stored energy is short circuited at a time and directed to a point, thus creating artificial lightning.

3. Battery terms

The main features that determine the performance of the batteries differ according to the chemical and physical properties of the batteries. Depending on the area of use, these features should be taken into consideration and battery

selection should be made accordingly in order to get the most performance from the battery. Battery performance characteristics are examined in the following subsections under the headings of battery capacity, energy, density, power density, efficiency, self-discharge, and battery cycle life.

Battery capacity

Battery capacity is defined as the total amount of electricity generated due to electrochemical reactions in the battery and is expressed in ampere hours. For example, a constant discharge current of 1 C (5 A) can be drawn from a 5 Ah battery for 1 hour. For the same battery a discharge current of 0.1 C (500 mA) can be withdrawn from the battery for 10 hours. For a given cell type the behavior of cells of different capacities with the same C ratio value is similar. The energy that a battery can deliver in the discharge process is called the capacity of the battery. The unit of the capacity is “ampere hour” and is briefly expressed by the letters “Ah.” The label value of the battery is called rated capacity. The capacity of a battery depends on the following factors:

To the number and size of plates in a cell: Essentially, the number of plates or the large size means that the amount of active substance that stores energy increases. The battery's ability to store or deliver energy will increase if the active ingredient in the battery plates is excessive. To the density of the electrolyte: If a high-density electrolyte is put in a battery, the capacity will increase to a certain extent. However, increasing density also means that the battery life is shorter. Therefore the electrolyte density cannot be increased as desired.

The two factors described earlier are related to the structure of the battery and are assigned to a battery that has been manufactured. Also, the capacity of a battery depends on its age. As the battery is used, the capacity decreases to a certain extent as a result of pouring the active substance from the plates, aging and wearing out of the elements forming the battery.

Electrolyte temperature: The capacity of a battery varies depending on the electrolyte temperature. Capacity increases as the temperature rises. Excessive heat causes wear on lead grates for lead–acid batteries. The worn grill rods come out and break. Therefore despite the capacity-increasing effect, batteries should not be exposed to excessive heat. Fig. 5.24 shows the relationships between the discharge voltage of a battery, discharge current, and discharge

capacity.

The top curves in Peukert curve indicate the voltage per cell when a battery is discharged within a certain current and time. The capacity curve shows how much of the rated capacity of the battery discharged with a certain current and time would yield. The discharge current curve explains how many amperes it must be discharged to achieve a certain capacity in a given time. The values apply to a new 100-Ah battery cell with full capacity at rated temperature. For a battery group the cell voltage values on the left should be multiplied by the number of cells, and for the batteries other than 100 Ah, the current and capacity values on the right should be taken into account.

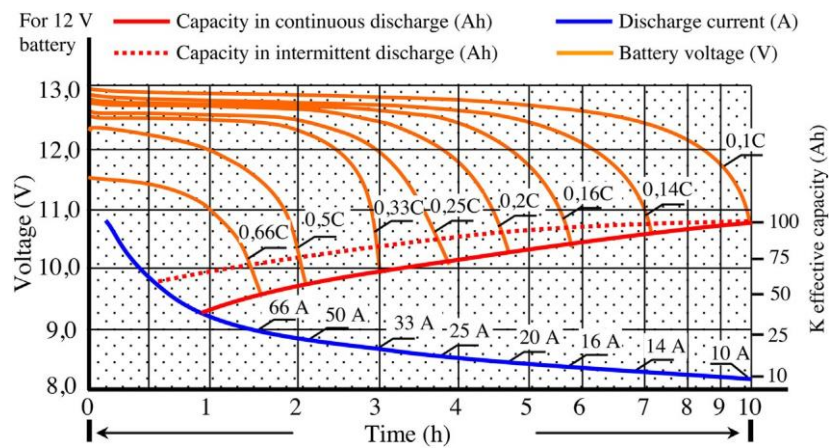


Fig. 5.24. Peukert curve based on discharge graph.

The higher the batteries are discharged, the lower the battery capacity. For this reason the charge and discharge curves of the batteries are exponential, not linear, as seen in the graphic. The next equation is given in the Peukert law.

$$C_p = I_B^k t \quad (5.2)$$

C_p (Ah) is capacity according to Peukert, I_B (A) is battery discharge current, t is discharge time, and k is Peukert constant. Battery manufacturers can give their capacity values in the sales catalogs, and the k value is approximately between 1.1 and 1.3.

According to the Peukert curve, this curve is used for a battery that is less than 10 hours discharge time. In the case of discharges over 10 hours, the discharge capacity is determined by dividing the battery capacity Ah by the current value drawn. For example, if a 100-Ah battery is discharged with 10

A, its voltage drops to 13 V immediately at the start of discharge, and after supplying energy for 10 hours, its voltage becomes 11.3 V.

Battery state of charge (SOC)

It is important for the user and the health of the battery to learn how much energy is left in a battery. The capacity of the battery is defined by the state of charge (SOC) as a percentage of reference. The amount of remaining energy in the batteries is usually set as SOC instead of giving in Coulomb, kWh, or Ah for easier understanding. The preferred SOC reference should be the SOC reference of the actual battery cell, not the capacity of a new battery cell. The capacity of a battery cell gradually decreases as the battery ages. For example, when a battery cell reaches the end of its life, its actual usable capacity is approaching 80 %. In this case, even if the battery is fully charged, its nominal SOC capacity will be around 80 %. Temperature and deep discharge currents further reduce the effective capacity of the battery. Reference SOC points are of great importance for the user to learn the battery SOC correctly. Battery SOC calculation is given by the following equation:

$$SOC = 1 - \frac{1}{C_B} \int I_B d\tau \cdot 100 \quad (5.3)$$

SOC must be between $0 \leq SOC(t) \leq 100$. C_B is nominal capacity of the battery, I_B is the current drawn from the battery. The battery should be operated within a certain SOC area in order for a battery to be charged/discharged properly, and the number of cycle life increases. The critical SOC operating band range of a battery is given in Fig. 5.25. When the battery is overcharged, it becomes disturbing for battery plates and can cause overheating. This causes the battery cell plates to wear and reduce their cycle life, such as not recharging. Therefore the battery should be operated in a safe SOC area in order to work properly and prolong its life. This safe working area varies according to the

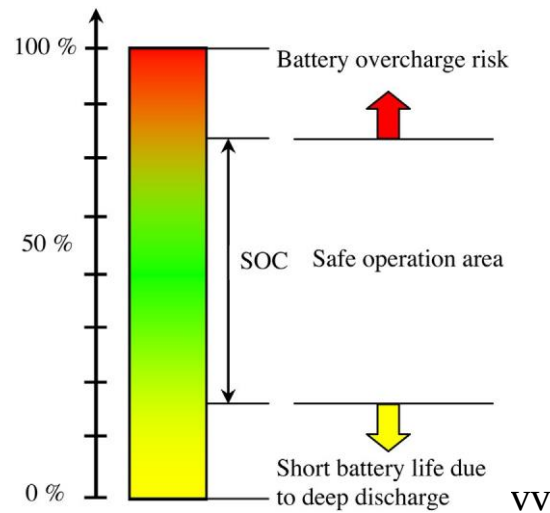


Fig. 5.25. Battery's SOC operating range.

Battery type, according to the technical specifications of the battery. Controlled charge and discharge equipment is required to hold the battery in this safe working area. By measuring the current and voltage of the battery real time, the battery operates in this specified SOC area. Fig. 5.26 gives the working band range according to the lithium-ion battery, and cell voltage is given for the charge and discharge conditions of the SOC safe working area. If the battery leaves the safe working area while it is charging, it causes the cell voltage to increase, to temperature up, and to decrease its life. If the battery leaves the safe working area while discharging, it causes the cell voltage to gradually decrease and damage the plates. In this case the battery cannot hold its first SOC in the next charge.

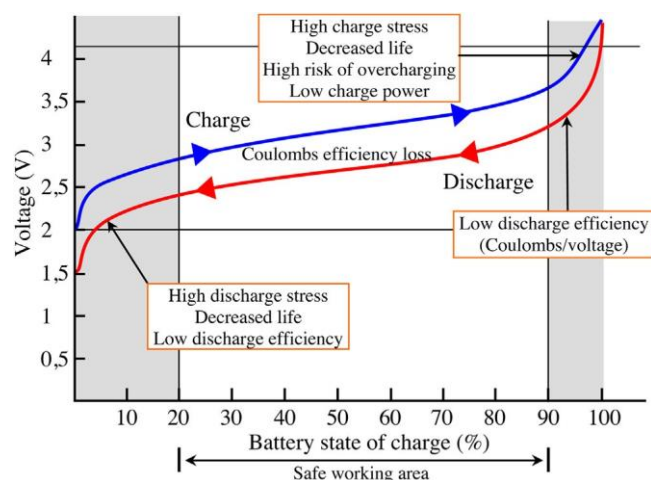


Fig.5.26. Cell voltage band gap for lithium-ion battery charge/discharge.

Effect of temperature on battery

The value of the ambient temperature during discharge is a factor affecting

the battery performance. As the ambient temperature decreases, losses in the output voltage increase and capacity decreases. The chemical reaction inside the battery occurs by the battery voltage or temperature. The chemical reaction will be faster in a high-temperature battery. The high temperature can accelerate the chemical reaction and the providing high performance in the battery. But at the same time, undesirable chemical reactions can occur and reduce battery life. The battery's shelf life and charge-keeping feature depend on the self-discharge of the battery. The self-discharge of the battery is an undesirable chemical reaction. Likewise, electrodes reduce the cycle life of battery as a result of negative chemical reactions such as corrosion and gasification. Therefore the temperature affects the battery's shelf life, cycle life, and the battery's charge-keeping ability. Fig. 5.27 gives SOC change in different discharge situations depending on the ambient temperature of a lead–acid battery.

Depth of discharge (DoD)

The amount of current that a battery can deliver during discharge is expressed by the depth of discharge (DoD). Fig. 5.28 gives the graph of the relationship between the number of cycles and DoD logarithmically. In other words, the battery cycle number is the exponential function of DoD. Fig. 5.28 gives the

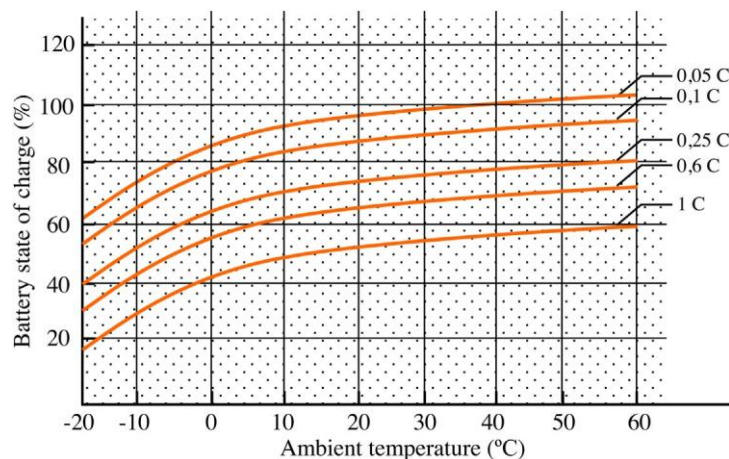


Fig. 5.27. Change of lead–acid battery capacity by temperature

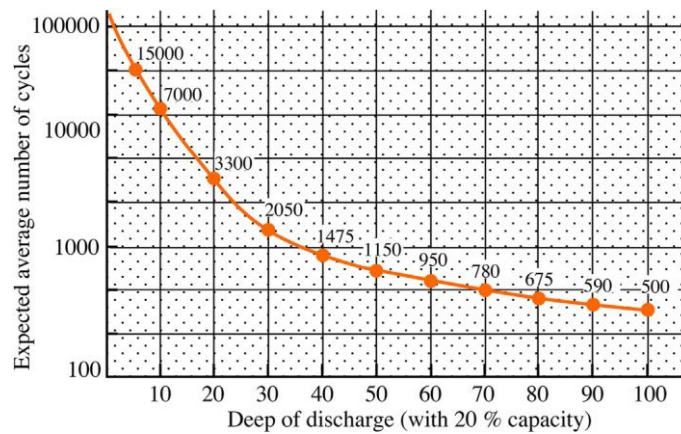


Fig. 5.28. Cycle number and depth of discharge for lead–acid battery

Relationship between the number of cycles and the DoD for the lead–acid battery type. But it is a typical model for all battery cell chemicals, including lithium-ion batteries with different scaling. This is because the battery life depends on the total energy efficiency that active chemicals can provide. The total energy flow is constant, when the 100 % DoD cycle is calculated as 1 cycle, 50 % DoD as 2 cycles, 10 % DoD as 10 cycles, and 1 % DoD as 100 cycles equivalent. In addition, because the cycle life and the performance of active chemicals decrease due to battery aging, the performance of the battery cells decreases.

Energy density

Energy intensity of a battery is determined as the amount of energy per unit weight or unit volume of the battery. Energy intensity unit is shown in Wh/kg or Wh/L. The energy density of a battery can be calculated in two different ways: theoretical and practical energy density. In theoretical energy density, the calculation is made taking into account the weight or volume of the anode, cathode and electrolyte, which are included only in the electrochemical reaction of the battery. In calculating the practical energy density, the total weight or volume of the battery is taken into account. In this case, depending on the battery type and manufacturing process, there can be up to five times the difference between theoretical and practical energy densities.

Power density

Another feature that characterizes battery performance is battery power density. Power density is determined as the amount of power per unit weight or volume of the battery. Its unit is W/kg or W/L. The power output of a battery depends not only on its chemical properties but also on its design and physical structure.

Therefore there is usually a trade-off between the power density and the

energy density during the battery manufacturing phase. For a battery with a high power density, low internal resistance and low electrode polarization are required. In order to achieve this, the amount of materials that do not react electrochemically should increase. This, in turn, increases the volume and weight of the battery, resulting in a reduction in energy density.

Efficiency

The efficiency of a rechargeable battery is calculated as the ratio of the total energy given by the battery to discharge to the total energy received by the battery. This rate may decrease up to 0.6 due to energy losses in the battery. Energy losses in the battery are caused by corrosion in the battery material, gas leakage in the electrolyte, battery internal resistance, and polarization losses in the electrodes. Battery charge numbers and battery life also affect battery efficiency.

Self-discharge

Another feature that characterizes battery performance is the amount of battery discharge when the battery is not used. Depending on the battery type and the ambient temperature, there are differences in the rate of unloaded discharge of the batteries. The battery can be fully discharged due to long-term use, and rechargeable batteries can be completely out of use. Therefore rechargeable batteries should be recharged at certain time intervals.

Cycle life

In rechargeable batteries, gas accumulation and leaks occur in each charge/discharge process, battery electrodes due to corrosion and corrosion, and chemical reactions in the electrolyte. As the number of battery charge/discharge increases, the internal resistance of the battery increases due to such structural defects and losses. Due to polarization losses, large drops in the output voltage occur while the battery is charged. As a result, the efficiency of the battery decreases. The battery becomes unusable after a certain number of charge/discharge cycles. There are differences in the number of battery charge/discharge depending on the battery types.

Lead–acid and LiFePO₄ battery DoD and temperature alarm graphics

The internal resistance of a typical lead–acid and lithium-ion battery is several m Ω (cylindrical-type lithium-ion battery internal resistance 10–50 m Ω , prismatic-type lithium-ion battery internal resistance 0.5–5 m Ω). This resistance value varies due to the chemical process taking place in the battery.

Cell voltage and current decrease due to battery resistance change. The resistance value mentioned here is not the $R = V/I$ resistance value we measure in ohms. This resistance for the battery cell is dynamic resistance. Dynamic resistance is defined as $R = \Delta V / \Delta I$. This resistance value, SOC, depends on temperature, battery charge/discharge current, and lifetime. In Fig. 5.29, internal resistance change of the cell according to current, temperature, SOC, and number of cycles is given.

In Fig. 5.29 A, the internal resistance is given which is high when the battery charge/discharge current is high. When looking at the change in temperature, it can be seen in Fig. 5.29 B that the internal resistance of the battery is high in the low-temperature environment and very low in the high-temperature environment. However, the limit temperature should never be exceeded. Otherwise, it may cause the battery to burst or burn from excessive heat. According to SOC, the internal resistance of the battery is high when the battery is fully charged and fully discharged. The graph showing low internal resistance of the battery in the active working area is given in Fig. 5.29 C. Finally, depending on the cycle life of the battery, the internal resistance change is given in Fig. 5.29 D. As the battery cell nears the end of its cycle life, it is understood that the internal resistance values are high and the life of the battery has expired.

Due to the internal resistance of the lithium-ion cell, the loss of $I^2 R$ in the cell is spent as heat. For example, when loaded with 1 C (2.3 A) for the M1 26500 LiFePO₄ cell model, its internal resistance is 10 mΩ. While the battery gives energy of $P = 2.3 \text{ A} \times 3.2 \text{ V} = 7.6 \text{ W}$, the lost power spent in the cell becomes $P = 2.3^2 \times 10 \text{ m}\Omega = 53 \text{ mW}$. Battery cell efficiency is between 99.3 % and 98.6 % while the battery is charging and discharging. Current and voltage limits are given in the safe working area of the M1 26500 LiFePO₄ in Fig. 5.30 and the Vision 6FM80 lead–acid battery in Fig. 5.31. While the battery cell is charging and discharging, the limit voltage of the cell should not be exceeded for the health of the electrodes.

Working temperature limits of M1 26500 LiFePO₄ in Fig. 5.32 and the Vision 6FM80 lead–acid battery in Fig. 5.33 are given in the safe working area. While the battery is charging and discharging, the operating temperature should

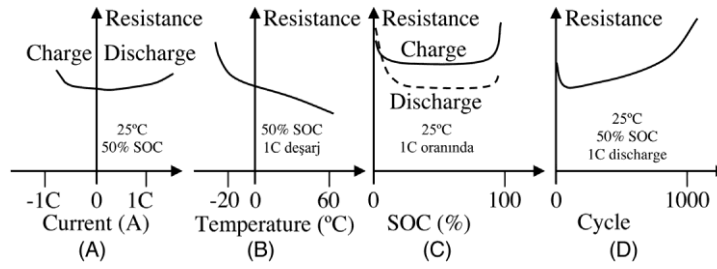


Fig.5.29 (A) Current, (B) temperature, (C) SOC, and (D) change of cell internal resistance according to the cycle parameters

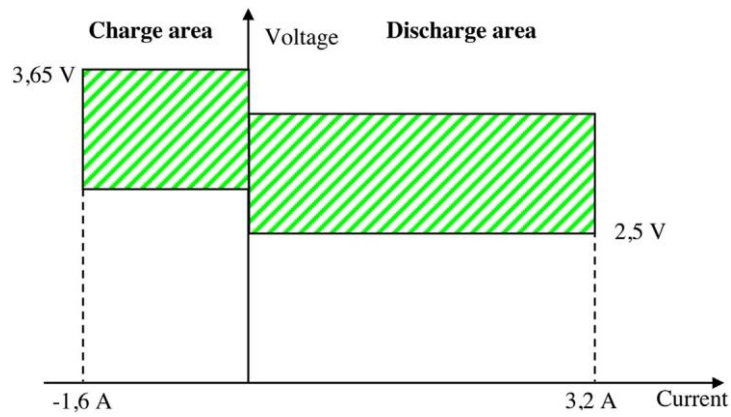


Fig 5.30. Safe charge/discharge working zone of LiFePO₄ battery.

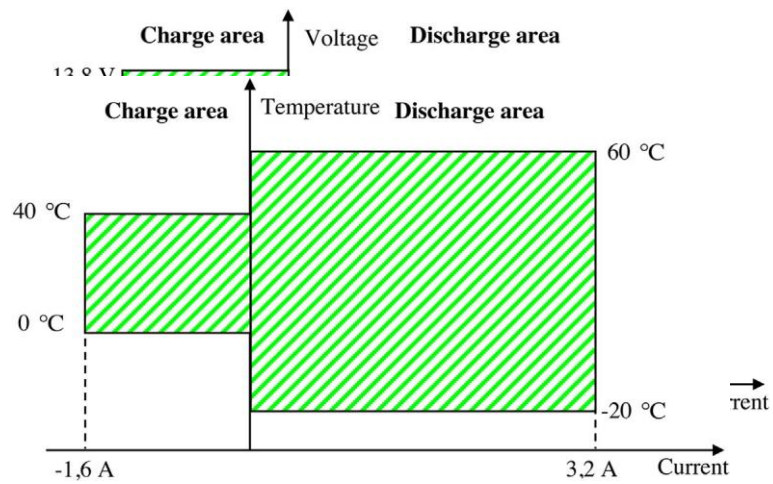


Fig.5.31. Safe charge/discharge zone of the Vision 6FM80 lead-acid battery.

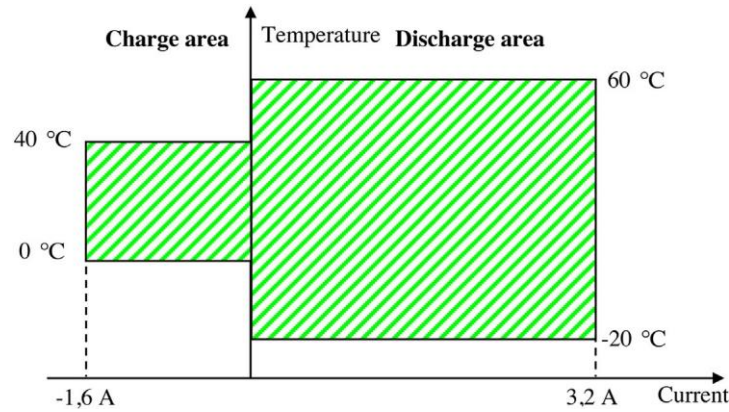


Fig.5.32. Safe temperature working zone of LiFePO₄ battery.

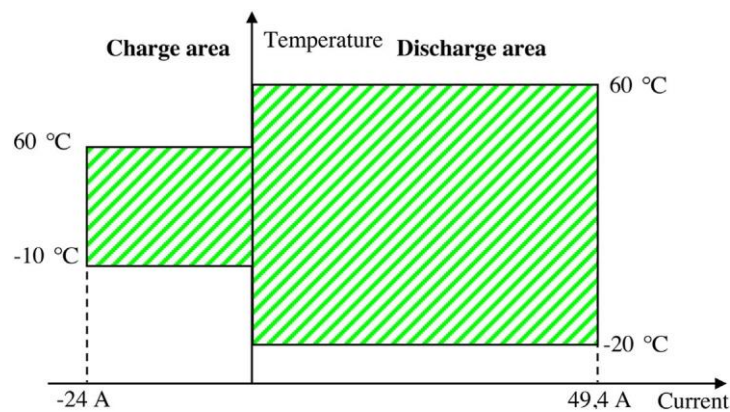


Fig. 5.33. Safe temperature zone of the Vision 6FM80 lead-acid battery.

Be within the limit range to avoid damaging the battery, dangerous situations such as explosion and fire.

Ultra capacitor terms

Ultra capacitors have some electrical parameters, just like batteries. These parameters vary depending on the chemical structure. Ultra capacitors with various chemical and physical structures, such as electrical double layer capacitors, pseudo capacitors, and hybrid capacitors, are common terms such as energy, each of which stores internal resistance. The capacity of an ultra capacitor is represented in F. The amount of energy it stores is shown in E_d and is expressed in Wh. The energy stored by an ultra capacitor is expressed as in the following equation:

$$E_d = \frac{1/2 C_{UC} V_{UC}^2}{3600} \quad (5.4)$$

C_{UC} is the capacity of the ultra capacitor, V_{UC} is terminal voltage. The amount of energy stored for the Maxwell brand BMOD0006 E160 B02 model

is calculated by the next equation:

$$E_d = \frac{1/2 \cdot 6F \cdot 160^2}{3600} = 21.3Wh \quad (5.5)$$

Equivalent series resistance (ESR)

The charge and discharge of an ultra capacitor depend on the movement of ions flowing through the separator from the electrodes to the electrolyte. Losses during this movement are measured as DC resistance.

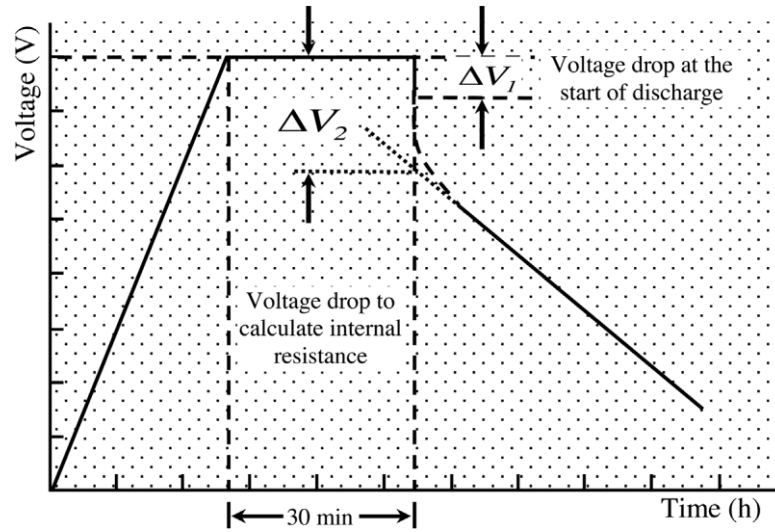


Fig.5.34. ΔV_2 voltage changes while calculating the ultra capacitor internal resistance.

The steps in the electrode pores can be shown with RC (resistance/capacitor) elements connected in series by making electrical circuit simulation. The increase of load-bearing layers in the pores causes an increase in internal resistance. DC internal resistance increases during charging/discharging depending on time. The internal resistance R_{ESR} can be calculated as in Eq. (5.6) with ΔV_2 voltage drop during discharge and the constant starting current I_{UC} ultra capacitor discharge current. ΔV_2 voltage drop variation is given while calculating the ultra capacitor internal resistance in Fig. 5.34.

$$R_{ESR} = \frac{\Delta V}{I_{UC}} \quad (5.6)$$

Effect of temperature on ultra capacitor

Temperature affects the internal resistance and capacity in the ultra capacitor, as in the batteries. Decreasing the temperature reduces the capacity

of the ultra capacitor and the efficiency of the ultra capacitor, because the chemical reaction rate in the separator part is reduced. The increase in temperature does not affect the capacity change of the ultra capacitor to a large extent, but after a certain temperature value it damages the ultra capacitor and separator plates. The effect of temperature on the internal resistance of the ultra capacitor is much more than the capacity change. While the internal resistance does not change at zero degrees and above, the ultra capacitor internal resistance increases at almost twice

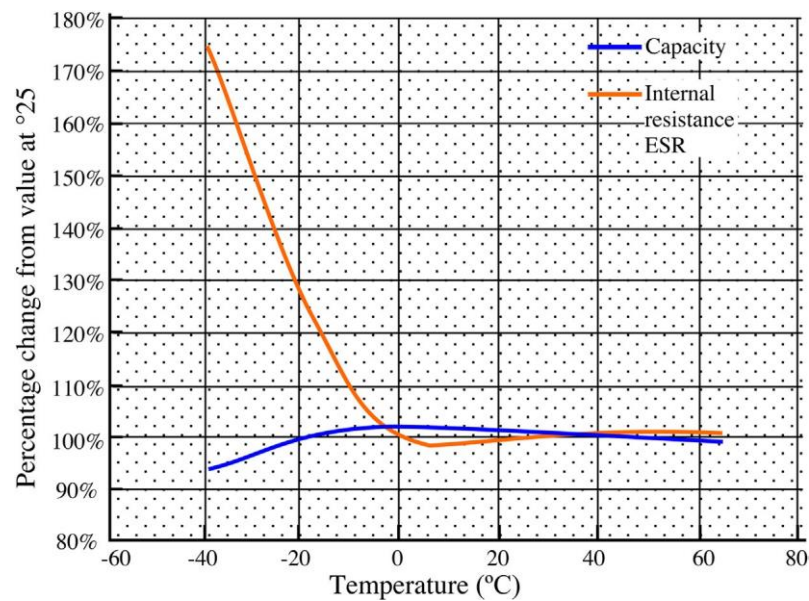


Fig.5.35. Internal resistance and capacity change of ultra capacitor with temperature.

At the temperature below zero. Fig. 5.35 is given the variation of the internal resistance and capacity of the ultra capacitor in terms of (%).

CONTROL QUESTIONS

1. What is the function of the positive electrode?
2. What is the function of the negative electrode?
3. Define an electrolyte.
4. What are primary-type batteries?
5. What are secondary-type batteries?
6. What is the function of a separator?
7. How does a battery operate (what is its working process)?

8. What is the current energy density of lithium cells today?
9. How does a lead–acid (Pb) battery work?
10. What is the structure of nickel–cadmium (NiCd) batteries?
11. What is the structure of nickel–iron (NiFe) batteries?
12. What is the structure of nickel–zinc (NiZn) batteries?
13. What is the structure of lithium–iron phosphate (LiFePO_4) batteries?
14. What is the structure of aluminum–air and zinc–air batteries?
15. What is the unit of measurement for energy density?
16. What is the unit of measurement for power density?

Chapter VI

SOLAR THERMAL SYSTEMS AND THERMAL STORAGE

6.1. Solar thermal systems

Solar energy has been used by humanity since the first years of history. Solar energy was first used for heating and later used for cooking. Thanks to the developing technologies today, solar energy is used in many different ways. Solar energy is directly converted into electrical energy with solar photovoltaic (PV) panels. Another method is to obtain high temperature with concentrated solar energy systems. It is used indirectly with a high heat transfer liquid. This method of use is for electrical energy generation and heating the residential. Concentrated solar energy systems are often used in large-scale applications. Concentrated solar energy systems do not require high technology like solar PV panels. It consists of reflectors and collectors with its general structure. The transport of heat is carried out with molten materials (molten salt) that can hold high energy density. The purpose of this is to increase system performance and efficiency. Electric energy generation topology with concentrated solar energy system is given in Fig. 6.1. In these systems the solar irradiation is concentrated and collected in a region. Then, this high-temperature fluid is transferred to the turbine system. Turbine is mechanically rotated with the high-temperature liquid converted into steam phase. Thus solar energy is converted into electrical energy indirectly. These systems are dependent on solar energy and solar energy systems cannot generate power during shadow and night hours. High thermal energy storage systems or auxiliary heaters are used to ensure the continuity of energy in these systems. One of the design parameters in these systems is determining the correct temperature. The correct temperature affects the turbine efficiency and performance that will operate in the solar system. There are many application methods in solar energy systems. The high temperature is obtained in the first method, while low temperature is obtained in the second method. These methods are parabolic trough collectors, linear Fresnel, parabolic dish collector, and central tower power system. Concentrated solar energy systems are explained in detail in Chapter 1, Solar System Characteristics, Advantages, and Disadvantages.

The solar irradiation is collected at a single point with reflectors in concentrated solar energy systems. Later, as in a traditional power plant, electrical energy is produced by generators using high steam.

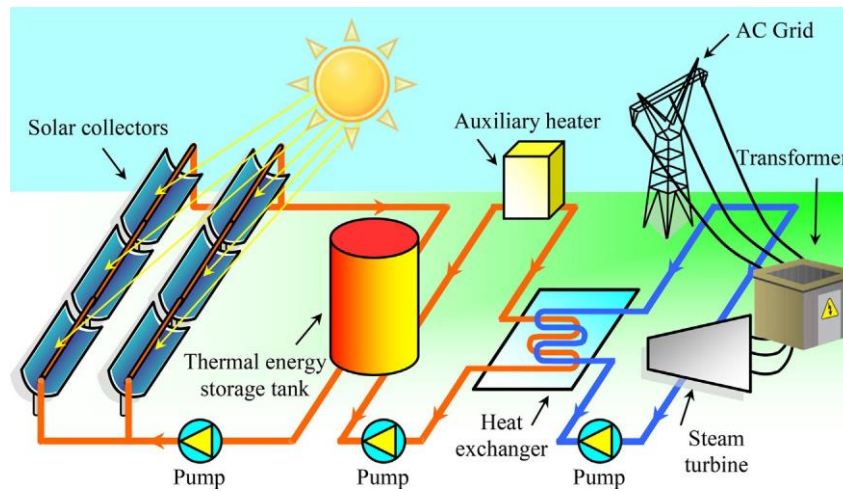


Fig.6.1. Electric power generation topology with concentrated solar energy system.

The purpose of concentrated solar energy systems is to capture a lot of solar irradiation. In these solar energy systems, more space is usually needed. Unproductive areas should be preferred during the selection of these areas. The most widely used method in terms of system efficiency and performance is parabolic trough solar energy systems. In addition, parabolic trough solar energy systems are long-lasting and have low maintenance requirements. Parabolic trough solar energy systems are used with energy storage methods. In these systems, molten salts are used as heat transfer liquid. The heat storage capacity of molten salts is much higher than normal liquids. Thus long-term high-temperature energy storage is possible. A large amount of energy is stored from the batteries with this energy storage method. Auxiliary heaters can be used to maintain the temperature of the stored heat energy. The energy source of these auxiliary heaters is renewable energy sources or thermal energy sources. Electrical energy needs can be met at any time with thermal energy storage solar systems. Since the amount of stored heat energy is in high volumes, both long-term and high-power demands are met with thermal energy storage systems.

6.2. Thermal energy storage

Due to the increase in energy need, humankind has caused the search for alternative energy sources. The use of energy resources that do not harm the environment and take their energy from nature is becoming widespread. Energy sources such as sun, wind, ocean, and biogas are among the most preferred renewable energy sources. Energy storage systems are seen as the most suitable solution due to the fluctuation of the power output of renewable energy sources.

The output of solar PV panels and wind energy are intermittent and unstable. Many energy storage methods are used to prevent this power fluctuation. Thermal energy storage method is used especially in solar energy systems. Thermal energy storage systems have a complementary feature for renewable energy sources like other energy storage systems. During periods of intense solar energy, solar energy is charged in the form of thermal. Then, when the system load demands power, the stored thermal energy is used with the help of steam turbines and discharged. The solar energy system, which has a thermal energy storage system in low solar irradiation times, has many benefits. High-capacity thermal energy storage systems are installed with low investment costs. In addition, the efficiency of thermal energy storage systems is high. Thermal energy storage systems can meet high power demands. Due to all these advantages, thermal energy storage systems become an indispensable part of renewable energy sources. Thermal energy storage systems can be evaluated for use in heating and cooling applications. Thermal energy storage systems are generally used in residential and industrial application areas. Accessibility and reliability are one of the important advantages of thermal energy storage systems. Thermal energy storage systems do not leave any negative environmental impact during the charging and discharging processes. Thanks to the high-power density of thermal energy storage systems, its use in the industrial area is increasing. Research continues on heat transfer materials in order to increase efficiency in thermal energy storage systems.

Studies are carried out to increase the amount of energy stored per unit volume or per unit mass in thermal energy storage systems. The purpose of these studies is to increase the power density of the stored energy. Phase-change materials are one of the most important factors in thermal energy

storage systems. Thus thermal energy storage system performance is increased and thermal energy storage volume is reduced. High steam pressure and corrosive heat carriers affect system performance and reliability in thermal energy storage systems.

Heat can be stored and used in two different ways in thermal energy storage systems. The first of these is that the hot water coming from the collectors is cooled by absorption systems and stored in cold form. The other can be directly stored in hot form. Heating and cooling processes in residential and industrial application areas are generally carried out using natural gas or electricity. Thermal energy storage systems are used to meet these needs. Solar energy is used in the most basic form for heating hot water in houses. This hot water requirement can be met by absorbing tubes and a thermal energy storage tank. The stored hot water is distributed to the house with the help of pipes. There are two different types as thermal energy storage mechanism. One of them is carried out using solid or liquid materials. In the other thermal energy storage mechanism, the phase change process is used. The collector life, system cycle number, storage volume, and heat leaks should be considered in storage design. To improve the thermal energy storage system performance, attention should be paid to the thermal capacitance effect of the storage tank.

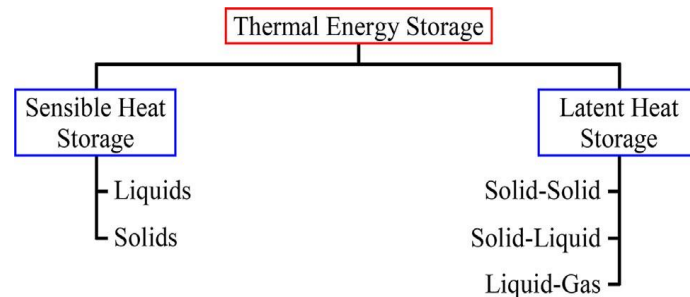


Fig.6.2. Thermal energy storage types.

The heat transfer liquid in the collectors must have a very high thermal capability. Although this heat transfer liquid varies according to the application type, generally, water, oil, water–salt, and water–glucose mixtures are used. The reason why water is used in thermal energy storage technologies is that it is low cost, environment friendly, and has a high thermal energy storage capacity. In addition, water is easy to transport with pumps and conventional pipes. It does not require a special installation for the thermal loop to circulate in the system. Another factor affecting thermal energy system efficiency is the location of the storage tank. The storage tank should be located where the system thermal losses are lowest. Placing the storage tank

away from the solar system will cause thermal losses during liquid transfer. The tank should be located in a place that is not affected by environmental conditions. The tank must be insulated with a well-insulated outer protection. Thermal energy storage systems are designed to be economical and with high power density. During system design, the optimum storage unit can be produced by using fluid dynamic methods and using simulation programs.

Thermal energy storage types are given in Fig. 6.2. The amount of energy stored in thermal energy storage systems is defined as capacity. This storage capacity varies depending on the storage process, system sizes, and thermal storage process. The ratio of the temperature reaching the user in the thermal energy storage system and the amount of solar energy coming to the collectors gives the total efficiency of the system. Losses in thermal energy storage systems generally occur as heat losses. It is desirable to store the thermal temperature in the storage system as soon as possible. The high energy storage density in the charge and discharge processes is a desired property in thermal energy storage systems. Thermal energy storage systems are carried out by two methods, thermal and chemical. It can be grouped into sensible heat and latent heat.

Sensible heat energy storage

Sensitive heat energy storage method is based on the principle of heating or cooling a liquid or solid material. The material to be used as heat energy storage is low cost. This method is often used for heating a residential or industrial Fig. 6.2 Thermal energy storage types application area. The charging and discharging processes of the sensitive heat energy storage system use the change in the heat capacity of material. In this method, no matter how well the storage system is isolated, there are always some losses. If the duration of the stored energy is long, the thermal insulation of the system should be done very well. The heat loss is directly proportional to the surface area and thermal heat storage material. Thermal energy storage systems are used using air, liquid, and underground storage in this method.

Air thermal energy storage system

Air–thermal energy storage, one of the sensible thermal energy storage methods, is widely used. Solid materials are used as hot air collectors. These solid materials are often inexpensive items that are easy to access such as rocks, gravel, and stones. The hot air is used in order to increase the internal

temperature of large buildings. Air–thermal energy storage systems are one of the cost-effective methods. The heated air coming from the heater can be used directly. Using gravel material, an air–thermal energy storage system can be installed with an insulated case and air inlet/outlet assembly. Many different designs are used in this method. The case walls can usually be products such as concrete or wood. The air inlet in the case can be horizontal or vertical. High efficiencies are obtained in both designs. The gravel dimensions, air flow, and case geometry used in this method are determined at the design stage. Phase-change materials and water are used in air–thermal energy storage systems. Phase-change materials and water have high thermal energy storage capacities. Air flow can be achieved with the structure designed using this thermal energy storage capacity. These designs increase the universality of use as they add functionality. Systems using water and phase-change materials are very compact. In addition, systems with water and phase-change materials are one-third lower than systems produced with gravel.

6.2. Liquid thermal energy storage system

The most commonly used material in liquid energy storage is water. Hot water tanks are used as thermal energy storage. Hot water tanks are cost-effective and their performance is high. In this technology, studies are carried out on tank insulations in order to increase the thermal insulation efficiency. Hot water tanks in liquid thermal energy storage systems are of two types, pressure and unpressurized. These systems include internal or external heat exchangers. Hot water tanks are made of galvanized, copper, and concrete materials. High insulation is an important parameter for all tank types. In pressure storage systems with heat exchangers, the exchanger is realized with a coil bundle. More than one hot water tank is used to increase the heat storage capacity. Thus the reliability of the system increases and the system continues to work in the case of fault. An additional pump is required for liquid circulation in external heat exchanger systems. The liquid thermal energy storage systems are generally designed unpressurised up to 30 m³. If the volume increases, it will be more appropriate to switch to a pressure design in terms of costs. The mains' water and pressure system fluid are independent and isolated from each other in pressure heat storage systems. The heat transfer process is carried out by using heat exchangers in pressure systems. Fig. 6.3 shows a solar collector structure with thermal energy storage. In this system

the liquid is heated by solar collectors and heat transfer is carried out with a heat exchanger. In these designs, hot water is usually taken from the top of the tank. The heated liquid is at the top, the cold liquid is at the bottom. Thus the cold liquid is heated by solar collectors. In this method the heat performance of the tank increases and hot water is always available. As a result, it increases the efficiency of the liquid thermal energy storage system.

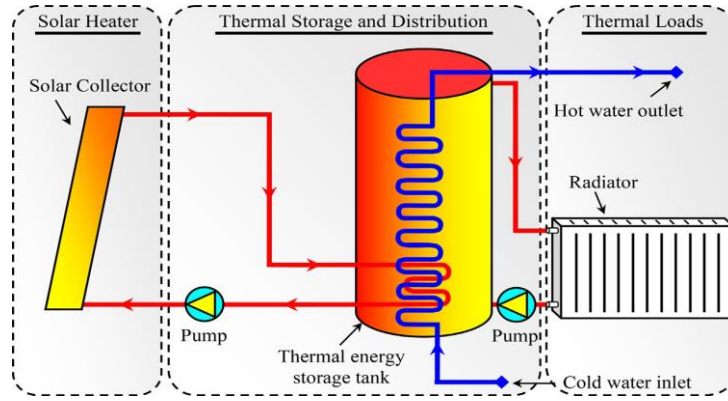


Fig. 6.3. A solar collector structure with thermal energy storage.

In liquid thermal energy storage systems, the stored energy capacity is calculated by the next equation, which is valid for water or any other liquid:

$$Q_{storage} = m_{liq} c_p \Delta t_s \quad (6.1)$$

Where $Q_{storage}$ is the heat capacity stored in t_s unit of time, m_{liq} is the mass of water or liquid, and c_p is the specific heat of water or liquid.

High heat capacity, easy installation, wide usage area, low cost, and renewable energy are among the advantages of these systems. These methods allow the installation of heat storage systems even in small scales. Thermal heat storage systems with solar collectors generally have seasonal usage characteristics. It is not possible to obtain hot water with these systems in winter.

6.3. Underground thermal energy storage system

Underground thermal energy storage systems are the most widely used methods to provide hot and cold storage. In this thermal energy storage system, rocks, soil, sand, and clay are used as storage areas. Pipes are placed to change the temperature of the thermal energy storage area. Heat transfer fluid is pumped into these drill pipes and the desired temperature is achieved. There is no thermal insulation in underground thermal energy storage systems. In these systems, only the floor is insulated. In this method the storage material such as

soil, rock, or sand performs heat transfer. These thermal energy storage systems are used in large-volume applications. Since the application volume is large, heat losses are reduced. These thermal energy storage methods are mostly used outside of residential areas. The ground in the application area should be suitable for the placement of drill pipes. These systems are also used for cooling large residential and industrial application areas during the summer months. In this use, cold energy storage is carried out by injecting cold fluid into the drill pipes. Another technique used in underground storage systems is cave or pit storage. Hot or cold water is pumped into these large underground caves or pits. Pumped water is discharged for later use. In this technique, heat losses occur at the point of contact with the water on the surface of the underground cave or pit. A natural underground cave or pit is generally preferred to use this technique.

Latent heat energy storage system

Latent heat energy storage system or phase change arises from the isothermal process in the storage material. In this storage technology, material density increases and volume decreases during energy storage. During the heat phase change process, heat exchange occurs directly inside the material. The latent heat energy storage method is the most effective way of thermally storing heat. High energy storage density is an advantage in this method. In this thermal energy storage method, the storage material can be solid–liquid, liquid–gas, and vice versa. The heat absorption or release occurs in this phase change process. The simplest example of a phase change is water. Water is solid at low temperature, liquid at medium temperature, and gas at high temperature. Fig. 6.4 shows the solar collector system with the latent heat energy storage. The part where latent heat is used is in the steam turbine part in this system. The water passes from liquid phase to gas phase. In the latent heat energy storage system, the melting point of the phase-change material should be in the desired temperature range. In this method, there must be a suitable heat exchange surface for the phase change process. The phase-change material must be compatible with the tank in which the heat will be stored. Materials and equipment used in the thermal energy storage system should not contain fire hazards.

Phase-change materials are classified as organic, inorganic, and eutectic. Organic phase-change materials can melt and solidify multiple times. A little crystallization occurs at high heat transitions. As an organic phase-change

material, paraffin waxes can be mentioned. Paraffin waxes release a large amount of heat during the crystallization process. Paraffin material is safe, inexpensive, and noncorrosive and can be used in a wide temperature range. Examples of nonparaffin organic materials include esters, fatty acids, and alcohols. These organic materials have high fusion temperatures and low thermal conductivity. Inorganic phase-change materials are generally used in high-temperature solar collector applications. One of the challenges of these inorganic materials is that they require constant maintenance. Inorganic materials freeze at low temperatures and are difficult to use at high temperatures. Salt hydrate can be given as an example of inorganic phase-change materials. Salt hydrates react with water at its melting point to disintegrate hydrate crystals. Salt hydrates have a high heat fusion per unit volume. Salt hydrates have low corrosive properties and are suitable for plastic tanks. Organic phase-change materials are flammable and have low thermal conductivity. On the other hand, inorganic phase-change materials are low-cost, abundant, nonflammable, and have high heat storage capacity. Eutectic phase-change materials are obtained by combining materials with both melting and freezing points. Eutectic materials have high thermal conductivity and their material density is quite high. Eutectic materials have low specific heat capacity.

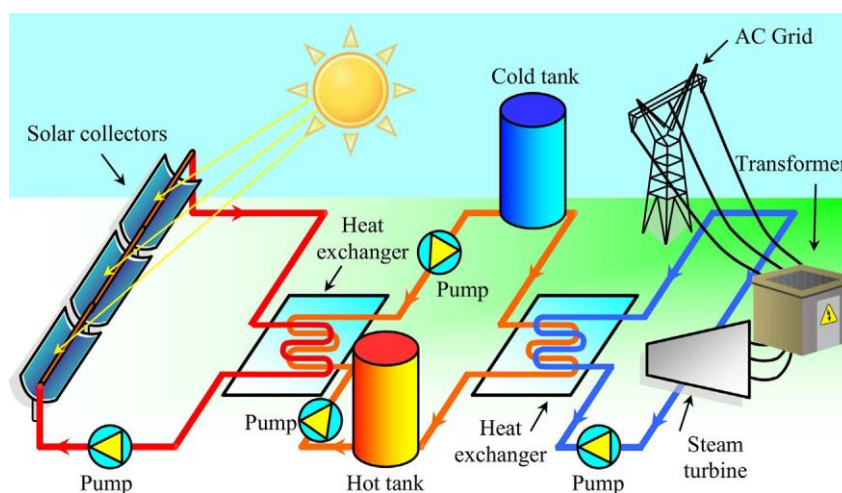


Fig.6.4. Solar collector systems with the latent heat energy storage.

Fig. 6.5 shows the temperature change graph in latent heat and sensible heat methods. When heat is added to a solid material, the temperature of the material increases until a phase change occurs. The molecular bonds break during phase change in solid material. Solid material passes from solid to liquid. If the amount of heat applied to the material increases after the phase

change takes place, the amount of heat stored by the material also increases.

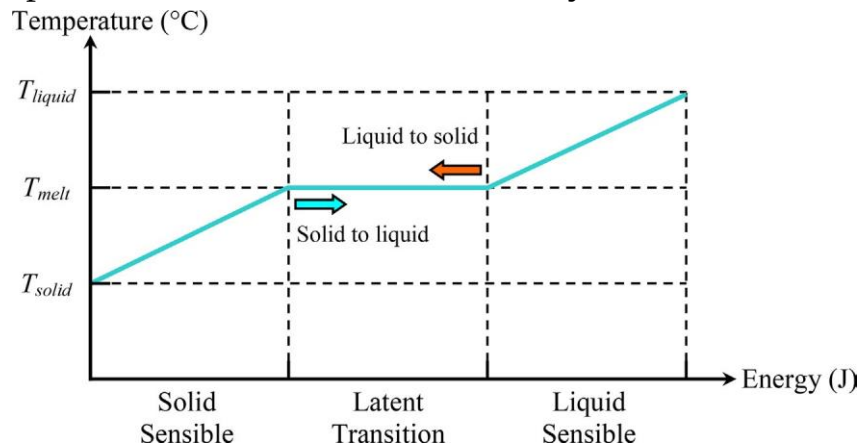


Fig. 6.5. Temperature change graph in latent heat and sensible heat methods.

6.4. Thermal energy storage systems economy and cost

Thermal energy storage systems are very cost-effective compared to other storage technologies. In terms of environmental impact, it is a clean energy storage technology. Thermal energy storage systems are a suitable storage method for large buildings. Thermal energy storage systems are generally used in small-scale applications for hot water and heating. It is also used in the field of electrical energy generation in large-scale applications. Thus electricity generation is realized with the stored heat energy during periods of intense power demand. Thanks to thermal energy storage systems, short-term high load demands can be responded quickly. Storage is made at high temperatures in thermal energy storage systems. While electricity is produced with high temperature, residential heating can be performed with the heat at the turbine outlet. Thus every process of thermal transformation is utilized. Thermal energy storage systems have low initial investment and maintenance costs. Thermal energy storage systems should be specially designed according to the application area. Compressor, pump, storage tank, and distribution lines are installed according to the application area requirement. Optimum thermal energy storage feasibility for the application site is achieved with a rational design. The peak loads in a region can be met with thermal energy storage systems. The thermal energy storage unit operator determines the peak load times and activates the system, thus reducing the load on the grid. In addition, the cost of electricity at high tariff rates is reduced by using a thermal energy storage system. On the contrary to this process, heat is added to the thermal energy storage system in the period when electricity prices are low. There is

no fuel cost in thermal energy storage systems with solar collector since the energy source is solar. Fig. 6.5 Temperature change graph in latent heat and sensible heat methods. Thermal energy storage systems are most commonly used to heat or cool a particular area. It is preferred for the water heating in residential or industrial application areas. Thermal energy storage is widely used in agricultural application, especially in greenhouses. It is also used in water pumping systems in the agriculture. Other areas of use are small power plants.

CONTROL QUESTIONS

1. How is solar energy converted into electrical energy?
2. What components are used in concentrated solar energy systems?
3. What does a concentrated solar energy system consist of?
4. How does a concentrated solar energy system operate?
5. Name the methods used in solar energy systems.
6. What is the working process of concentrated solar energy systems?
7. Is the energy produced by solar photovoltaic panels and wind turbines stable?
8. What are the advantages of solar systems that store thermal energy during periods of low solar radiation?
9. Why is the use of thermal energy storage systems in the industrial sector expanding?
10. How many main mechanisms of thermal energy storage exist?
11. On what principle does the rational thermal energy storage method operate?
12. How is thermal energy storage through air implemented?
13. How many types of hot water are used in liquid-based thermal energy storage systems?
14. What materials or formations are used as storage fields in underground thermal energy storage systems?

Chapter VII

HYBRID ENERGY STORAGE AND INNOVATIVE STORAGE TECHNOLOGIES

7.1. Hybrid energy storage systems

Due to the nature of renewable energy sources, their output power varies depending on natural conditions. Energy storage systems are the most suitable solution for the intermittent output power characteristic of renewable energy sources. The high power and energy density of energy storage systems supports the use of renewable energy sources. Sources and energy storage must be used together if a reliable renewable energy power system is to be established. Thanks to today's technological developments, energy storage units can supply 1–100 MW power for a long time.

Energy storage systems mainly consist of four types: electromagnetic, electrochemical, mechanical, and thermal. The classification is made according to material technology and methods used in energy storage units.

The energy storage technology desired to be used in an energy production facility should be determined by considering the performance–cost parameter. Systems established to meet energy needs must meet the long-term energy need as well as sudden load demands. Technologies that respond to power needs are energy storage applications that are used specially to improve power quality. Energy storage applications are used to ensure the constant of the grid frequency, to prevent sudden load changes and voltage fluctuations. In these dynamic power applications, while the response time should be in the millisecond level, the required load power demand may be in the minutes or hours.

The capacities of energy storage systems can meet the needs in various time intervals such as seconds, minutes, hours, and days/months. The unique structures and characteristics of energy storage systems create these time periods. The usage areas of different energy storage systems, the amount of power they can store, and their durations are compared in Fig. 7.1. Compressed air and pumped hydroelectric energy storage systems are a storage technology that can meet the load requirement on a day/month basis. These high energy density storage systems are used to support the grid. In addition, superconducting magnetic and hydrogen energy storage systems are also used

to support the grid. However, in terms of energy transfer times, the

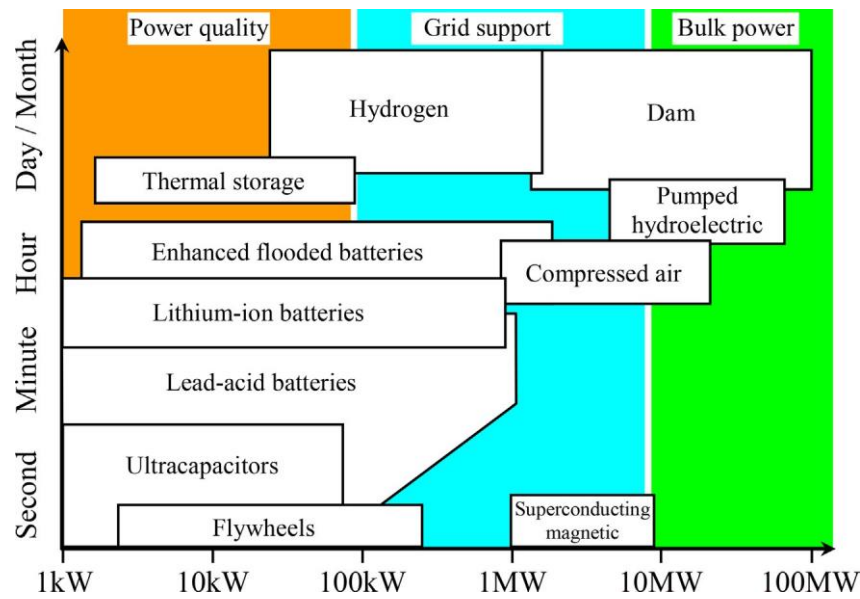


Fig.7.1. The comparisons of energy storage technology

Superconducting magnetic energy storage system can provide support for a short time (second), while the hydrogen energy storage system can provide energy on a day/month basis. Fluid batteries are used in long-term and high-energy systems. Nickel–cadmium, lead–acid, and sodium–sulfur battery technologies are used in areas where high power density is required. Lithium-ion batteries are widely used in portable device applications that require high energy density and in applications where energy storage efficiency is important. The ultra capacitor energy storage system is generally preferred in power quality improvement studies. Flywheels and ultra capacitors have higher power density compared to batteries. They can be charged or discharged very quickly at high currents. However, flywheels and ultra capacitors do not transfer energy for a long time as they have low energy density compared to batteries.

Hybrid energy storage with battery and ultra capacitor

A hybrid energy storage system is created with the energy storage unit obtained by using two or more energy storage systems together. These energy storage units reveal a complementary structure with their performance characteristics. Battery: it is a more cost-effective energy storage technology compared to other storage types. In addition to being able to provide energy for a long time, batteries can also meet sudden power needs (limited discharge current rates). However, as the batteries are deeply discharged in the case of

sudden power demands, their cycle life decreases rapidly. While the energy storage process

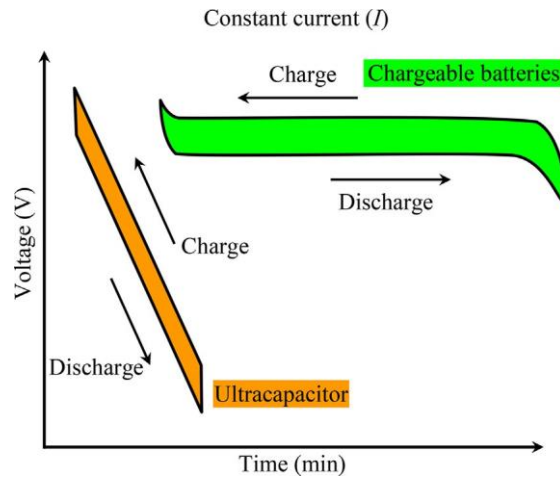


Fig. 7.2. Charge/discharge of battery and ultra capacitor graph.

Takes place electrochemically in a battery, energy storage in the ultracapacitor occurs with a static charging event. Because of these features, ultracapacitors are an energy storage unit with higher power density compared to batteries. Due to these features of the battery and the ultracapacitor, it would be reasonable to combine these two storage technologies for high power and energy needs. The battery and ultracapacitor can be charged/discharged simultaneously thanks to the power electronics converters. The time-dependent voltage change rates of the battery and ultracapacitor storage units are given in Fig. 7.2. While the battery provides energy for a long time, the ultracapacitor can provide energy in a short time.

Hybrid energy storage system consisting of battery and ultracapacitor will be the most appropriate solution to meet the load requirement when instantaneous and long-term power is required on the demand side. Batteries have a power density of 10–1000 W/kg with today's technology, while ultracapacitors have a power density of 10–106 W/kg. When the hybrid energy storage system is used, the ultracapacitor will support it by meeting the demand power that the battery characteristic is insufficient. Thus the cycle life of the batteries that are not operated at high discharge currents will be extended.

Ultracapacitors or supercapacitors are electric double-layer capacitors. Ultracapacitors are electrochemical storage elements that can allow high charge and discharge currents. High charge/discharge current rates have become a remarkable field of study, especially for electric vehicles, which are becoming widespread today. They are used with batteries in renewable energy sources and distributed energy applications. Ultracapacitors have high costs

compared to other battery devices. If the costs of ultracapacitors decrease, their use will become widespread. Ultracapacitors have high power densities and high charge/discharge cycles. Electrode types used in ultracapacitors have carbon technology and are different from ordinary capacitors. Thanks to this technology, a larger surface area is provided in the electron flow. Although ultracapacitors store very low energy compared to batteries, their cycle life is quite high. These specifications make ultracapacitors the energy storage unit of the future. Studies are carried out on ultracapacitors within the scope of longer charge/discharge times. High and fast charge/discharge currents will expand the use of ultracapacitors in distributed grid infrastructure in the future. In other possible situations, there will be long-term load demands. In such a case, it will not be sufficient to use only a low energy density ultracapacitor unit. Batteries have 100 times more energy density compared to ultracapacitors due to their structure. Therefore it would be a suitable solution to use a high energy density battery unit together with the ultracapacitor unit.

Batteries are used in many different applications. These energy storage technologies have some disadvantages. Batteries have a limited depth of discharge and their cycle life decreases depending on the amount of use. Ultracapacitor energy storage units do not contain this negative specification. At the same time, ultracapacitors have fast response times. In addition, ultracapacitors are more resistant to high temperature and vibration than batteries. Ultracapacitors are widely used in transportation areas such as electric underground trains. Energy transmission lines have been eliminated by integrating the ultracapacitor to the underground train. Trains charge quickly during the passenger dropoff and pickup. It can move forward with the energy stored to the next stop. Ultracapacitors are used in braking times in electric vehicles. When vehicles with large masses are stopped in a short time, high powers arise instantly. This high-power value cannot be stored in batteries in a short time. But ultracapacitors can store this energy with their characteristic structures. Thus they contribute to energy efficiency in the field of transportation.

Solar photovoltaic (PV) panels and wind energy are renewable energy sources with intermittent and time-dependent variable output characteristics. A hybrid energy storage system with battery and ultracapacitor can ensure the continuity of energy. The hybrid energy storage system helps to increase the cycle life of the batteries and to be used at maximum performance. Especially

in off-grid power generation systems, the continuity of energy is provided. The application topology of the hybrid energy storage unit to the solar system is given in Fig. 7.3.

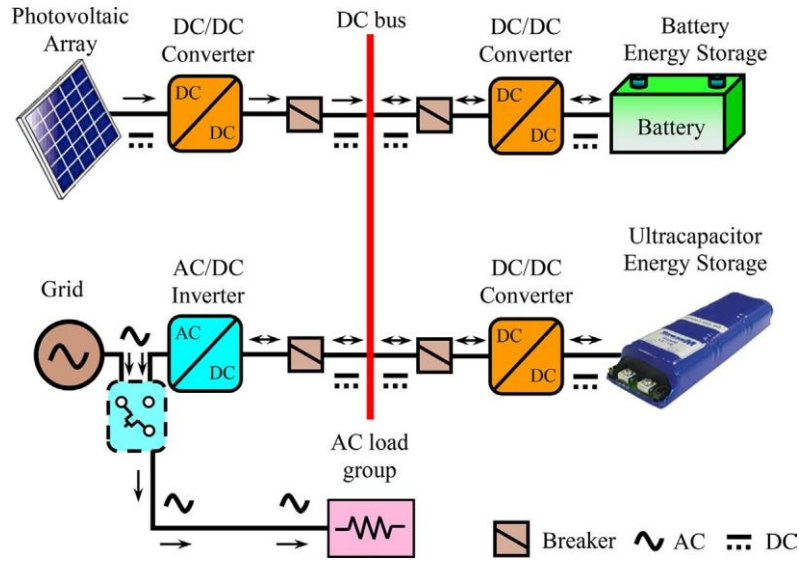


Fig. 7.3. The topology of hybrid energy storage and solar PV panel system.

A good system performance is ensured by creating a hybrid energy storage system consisting of battery and ultracapacitor. By using the hybrid energy storage system consisting of battery and ultracapacitor, both the volumetric dimensions of the battery can be reduced and a longer charging state can be achieved. Ultracapacitors have a high-power density compared to batteries. Therefore ultracapacitors can meet the high-power demand in a shorter time. Batteries have a higher energy density than ultracapacitors. These features can meet the long-term energy needs of the batteries. In the hybrid energy storage system, the ultracapacitor meets the sudden power demand, while the battery meets the long-term or continuous power demand.

7.2. Ultracapacitor EPR calculation experiment

When the ultracapacitor is not used, its energy decreases by itself and the voltage value decreases to zero. This situation is represented in the ultracapacitor by an equivalent parallel resistance (EPR). EPR calculation experiment of Maxwell brand BMOD0006 E160 B02 model ultracapacitor was performed in this chapter. First, the ultracapacitor was charged at a voltage level of 15 V. Then, the voltage value was recorded with certain time periods. These period intervals have been chosen as 10 minutes. As indicated in Fig. 7.4, voltage values were recorded for 1734 minutes.

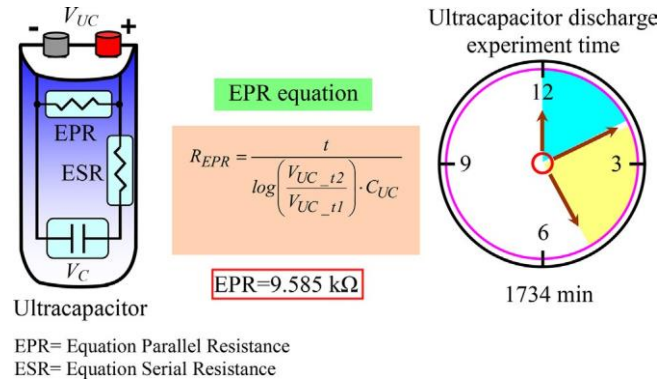


Fig. 7.4. The experiment of ultracapacitor EPR.

The voltage value decreasing over time due to the EPR in the ultracapacitor is calculated by the next equation:

$$V_{UV_t2} = V_{UV_t1} - \frac{t}{R_{EPR} \cdot C_{UC}} \quad (7.1)$$

Where V_{UC_t2} is the voltage value of the ultracapacitor read at time t_2 , V_{UC_t1} is the voltage value of the ultracapacitor at t_1 , t is total experiment time, R_{EPR} is ultracapacitor equivalent parallel resistance, and C_{UC} is the total capacity amount of the ultracapacitor in F. This EPR value found in the ultracapacitor electrical circuit is calculated by the next equation:

$$R_{EPR} = \frac{t}{\log\left(\frac{V_{UC_t2}}{V_{UC_t1}}\right) \cdot C_{UC}} \quad (7.2)$$

The EPR value of the ultracapacitor with 15 V 58 F capacity used in the experimental studies was calculated as 9.585 kΩ.

This equivalent resistance causes a continuous leakage current to flow through the ultracapacitor and, over time, the ultracapacitor voltage leads to an end. It is seen that the voltage value decreases over time due to the EPR of the ultracapacitor in Fig. 7.5. The voltage value at the beginning decreases rapidly in the first moments. The voltage value decreases to 12.44 V at the end of 1734 minutes. If the EPR of the ultracapacitor is large, the leakage current of the ultracapacitor is also small. This also determines how long the ultracapacitor can hold above the amount of stored capacity. As a result of the EPR experiment, it was observed that the ultracapacitor had a total voltage drop of 2.56 V within 1734 minutes. When a general ratio is established for the ultracapacitor voltage to reach 0 V, it takes approximately 7.05 days for

the amount of stored capacity to be finished.

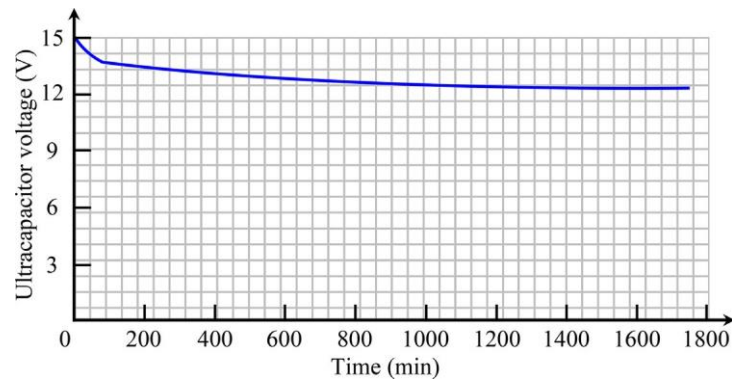


Fig. 7.5. Ultracapacitor EPR experiment VUC_tchange

7.3. Innovative energy storage technologies.

Gravity energy storage

The energy storage method can be realized using the force of gravity. A force is exerted by gravity on an object of a certain weight. At first, clock pendulum applications were made using the gravity force. An energy storage and energy production can be realized using gravity. The most important parameters in these applications are mass weight and height. The energy to be obtained from the gravity force is calculated by the next equation:

$$E_{gra} = mgh \quad (7.3)$$

Where m is the weight of the mass to be used as a storage unit, g is gravity constant (9.80665 m/s²), and h is height at which the mass will be moved. Gravity energy storage application can be used especially with renewable energy sources. For this energy storage technology, a mass with a high weight (>3000 t), a channel opened underground, reducer system, pulley system, and generator units are required. Gravity energy storage system is a mechanical storage method. The mass is raised with excess energy produced from renewable energy sources in this energy storage method. The up movement of the mass is carried out by a motor and reducer system. Thus energy will potentially be stored in the system (charged). In the case of energy need, the mass will be released by the gravity force and move down the channel. Meanwhile, electricity will be produced with the generator. Renewable energy-based gravity energy storage system topology is given in Fig. 7.6. Since battery energy Storage units are compared, these systems can store and

provide high energy. The high-power charge/discharge rates are not possible in batteries. The cycle life of the batteries decreases and problems such as excessive temperature occur in this situation. There is no problem with cycle life in gravity energy storage system. In addition, sudden high-power values can be provided with gravity energy storage systems that are predicted to have a service life of up to 50 years with periodic maintenance. Gravity energy storage system provides flexibility in terms of use. It can be used at any time of the day. In addition, start-up of the system is very fast. Thus the gravity energy storage system has a fast frequency response. The gravity energy storage system provides a great advantage with a response time of less than 1 second at full load. Opening a high depth channel for gravity energy storage system installation is high in terms of initial setup cost. Since it has a mechanical structure, it needs periodic maintenance.

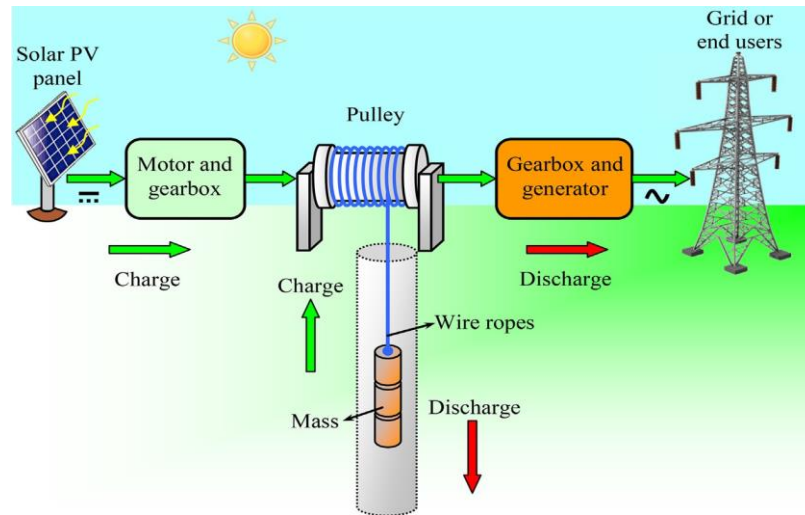


Fig. 7.6. Renewable energy–based gravity energy storage system topology.

Flywheel energy storage

One of the mechanical energy storage methods is flywheel. It was one of the energy storage methods used by establishing a motor and generator system before chemical energy storage technologies. Basically, flywheels have a very simple working logic. Energy is stored rotatable in a rotating mass. When energy is needed, electrical energy is provided by coupling the rotating mass with the generator. The energy stored in the flywheel energy storage system is calculated by the next equation:

$$E_{fly} = \frac{1}{2} \int p(x) r^2 \omega^2 dx \quad (7.4)$$

The amount of energy stored in the rotating mass depends on the density of the rotating axis ($\rho(x)$), the diameter of the rotating mass (r), and the square of the angular velocity of the rotating mass shaft. Fig. 7.7 shows the power capacity comparison of the flywheel energy storage.

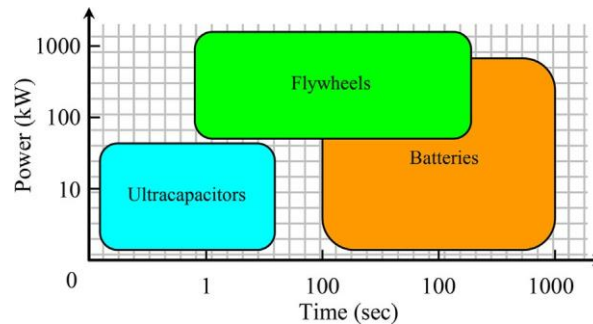


Fig. 7.7. Power capacity comparison of flywheel energy storage.

The flywheel energy system has a fast response time compared to electrochemical energy storage systems. It is used in grid power cuts with this feature. Thanks to the power electronics and composite material technology, the flywheel energy storage system performances are increasing. In conventional flywheel energy storage systems, a motor is connected to a rotating mass shaft and the motor performs energy storage. Energy is taken with another generator connected to the rotating mass (discharge). With the developments in power electronics, the same process is carried out with a single motor/generator. The system efficiency is increased by providing bidirectional energy flow thanks to the power electronic circuits. Flywheel energy storage unit capacities can be increased by increasing the material moment of inertia or by higher rotation speeds. The material moment of inertia can be realized using design and composite material. In some applications the inside of the rotating mass is hollow and the bulk density is concentrated on the outer diameter. Thus the weight of the rotating mass is reduced by design. Flywheel energy storage systems have a moving and rotating structure. Friction is minimized by using a magnetic system in the bearing of the rotating body. In addition, the environment with the rotating object is vacuumed, and the air friction during rotation is reduced. All these improve the performance of the flywheel energy storage system. One of the methods used in flywheel energy storage systems is that a mass with a large radius is increased up to several thousand cycles. Energy storage can be provided by using a conventional motor and power electronics circuits. This

method is generally used in large flywheel energy storage systems (heavy mass). In this method the rotation speed of the rotating object is not high. Energy storage is performed by radius and weight parameters in this method. Fig. 7.8 shows the integration of the flywheel energy storage system with the grid. In this method the stored energy is transferred to the grid by a generator, alternative current (AC)/direct current (DC) rectifier circuit, and DC/AC inverter circuit.

Another method used in flywheel energy storage systems is to store energy with high speed. In this method the rotating object is rotated up to 100,000 rpm. The rotating object weight is low in this method. This method is used in small applications in terms of volume and weight. Small applications connected in parallel can be used instead of large flywheel energy storage systems. There are losses due to air friction and bearing in flywheel energy storage systems. These cause energy losses with self-discharge in the flywheel energy storage system. The high speeds have been achieved in the rotating body with the developments in the field of composite materials. Composite material technology has enabled it to work with low losses, especially at high rotational tip speeds. The very high speeds are achieved with permanent magnet brushless DC motors. Power electronics converter circuits enable motors to operate at high speeds. In addition, bidirectional energy flow is provided by a single-power electronic converter.

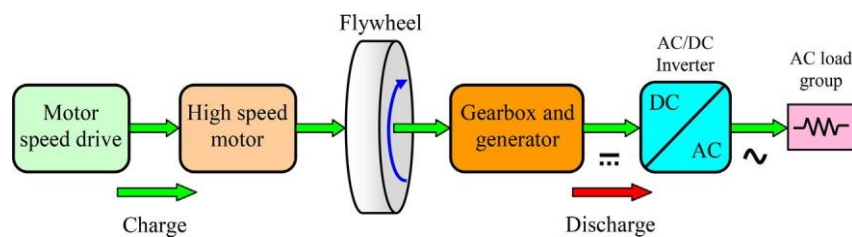


Fig. 7.8. Flywheel energy storage system topology.

Flywheel energy storage systems have high power density. They can provide very high powers sudden thanks to these features. Flywheel energy storage systems allow high charge/discharge powers. Flywheel energy storage systems do not cause environmental pollution since they have a mechanical technology. Their efficiency is high during energy storage and energy transfer (>90 %). The performance of flywheel energy storage systems operating in magnetic bearing and vacuum is high. Flywheel energy storage

systems have a long working life if periodically maintained (>25 years). The cycle numbers of flywheel energy storage systems are very high (>100,000). In addition, this storage technology is not affected by weather and climatic conditions.

One of the most important issues of flywheel energy storage systems is safety. As a result of mechanical failure, the rotating object fails during high rotational speed poses a serious danger. One of the disadvantages of these storage systems is noise. It is generally located underground to eliminate this problem.

Superconductive magnetic energy storage

Superconducting materials are the state in which the electrical resistance of the material is zero, and the magnetic exchange fields disappear. This case occurs when cooled to temperatures below a characteristic critical temperature. In superconducting magnetic energy storage systems, electrical energy is stored as a magnetic field in the form of DC. Fig. 7.9 shows the superconducting magnetic energy storage system topology.

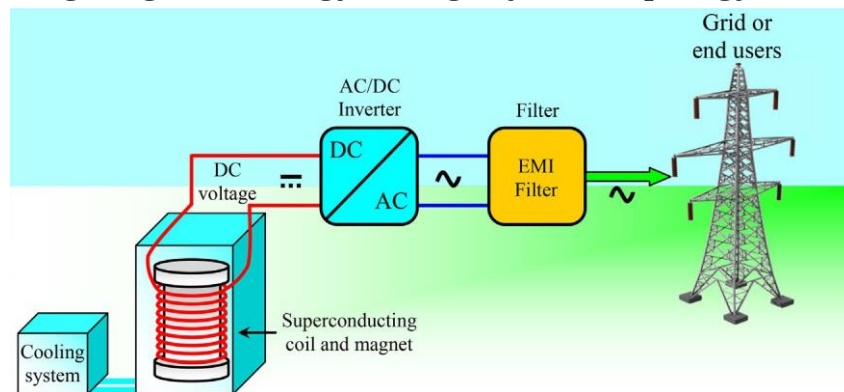


Fig. 7.9. Superconducting magnetic energy storage system topology.

The electrical energy is obtained by moving the coil group around an electromagnetic field. This electric energy produced is explained by the principle of magnetomotive force. The voltage value induced in a coil group is calculated by Eq. (7.5). The amount of energy stored in a coil group is calculated by Eq. (7.6). According to this equation, the amount of stored energy varies depending on the inductance value and the square of the current. The energy density obtained in a magnetic field in the superconducting magnetic energy storage system is calculated by Eq. (7.7). The high energy density values can only be achieved with high current values in the superconducting magnetic energy storage system.

$$e_{emf} = -N \frac{d\theta}{dt} \quad (7.5)$$

$$E_{(t)} = \frac{1}{2} Li_{(t)}^2 \quad (7.6)$$

$$E_{mag} = \frac{B^2}{2\mu} \quad (7.7)$$

In the superconducting magnetic energy storage system, special alloyed (niobium–titanium) conductive wires are used to create a high-density magnetic field. The current carrying capacity of the conductive wire varies depending on the temperature and magnetic field. Closed vessel and low-temperature environment with vacuum provide this working environment. The electrical resistance reaches a very low value at this critical temperature value. In order to maintain a superconductor's environment, the temperature must be cooled to approximately 269 °C.

The superconducting magnetic energy storage system is an important technology to ensure proper power quality and increase the penetration of renewable resources. Superconducting magnetic energy storage offers significant advantages, including fast response time from standby to full power.

It has the power capacity of superconducting magnetic energy storage systems (1–10 MW). Superconducting magnetic energy storage systems have a fast discharge structure at nominal capacity. The response time in this energy storage technology is around milliseconds and it is a long-life energy storage system. Despite the low maintenance costs, the installation cost is high. There is no heat loss due to resistance and system efficiency is high in this energy storage technology. Energy is stored magnetically in the form of DC current in superconducting magnetic energy storage systems. It is sufficient to use a DC/AC inverter power circuit to connect to the grid. It has no harmful effect on the environment during the energy storage system operation. The long conductors are needed to storage energy at high powers in this energy storage system. In order for the energy storage system to operate in the superconductor state, it must be continuously cooled. With the recent developments in technology, low temperatures can be obtained by using liquid nitrogen.

CONTROL QUESTIONS:

1. Into how many main types are energy storage systems divided, and what are they?
2. What types of batteries are used in long-term and high-energy storage systems?
3. Which types of batteries are used in applications requiring high power density?
4. How is a hybrid energy storage system created?
5. What are the functions of the battery and ultracapacitor in a hybrid energy storage system?
6. What power density do batteries and ultracapacitors currently have with today's technology?
7. What is the main advantage of ultracapacitors compared to batteries?
8. How is the voltage drop over time due to ESR (Equivalent Series Resistance) in an ultracapacitor calculated?
9. What type of storage method is the gravitational energy storage system?
10. What is required for the implementation of gravitational energy storage technology?
11. How does a flywheel energy storage system operate?
12. How does the superconducting magnetic energy storage (SMES) system work?
13. What is the power range of superconducting magnetic energy storage systems?
14. What temperature must be maintained to preserve the superconducting state?

Chapter VIII

SOLAR HYBRID SYSTEMS FOR SMART GRIDS

8.1. Smart grids and solar hybrid systems

When electrical energy was introduced in a usable form in the late 19th century, it was in the form of regional power plants that only served consumers. Although power consumption and production were in certain regions, long-distance transmission was not in question. As the demand requirement increased, so did the distribution grid line gradually. The grid systems are primarily isolated from each other and connected to each other from a single point. Fig. 8.1 shows the basic operating structure of the conventional electricity grid. Electricity is produced in large power plants that transfer the electricity to the transmission line with the help of step-up transformers to carry it over long distances. The electrical energy in the transmission lines is reduced to the voltage level in the distribution line with the step-down transformers and transmits it to the end users. While the basic operating structure of the grid has generally remained the same for many years, the application structures used for its planning and operation have changed over time. Taking into consideration the amount of energy demanded in the conventional electricity grid, the control of electrical energy is ensured by the power plants coming into operation.

There are large power plants that meet the basic demand power and peak power plants that activated at peak demand times. Especially the operating costs of peak power plants are quite high and this affects the total operating cost.

Smart grid structures

Smart grid can be defined as the fact that all units or nodes (such as production units, transformer centers, distribution centers, and consumption units) in the electric power system are active, adaptive (able to adapt to changing conditions), flexible, and have a strong structure that any production or consumption unit can easily be connected. In addition, smart grid can display the operation of all interconnected components, from central and distributed production facilities to high voltage lines to industrial users, energy

storage applications, end users, and electric vehicles. Existing transmission and distribution networks are not designed in the smart grid logic. The requirements of smart grids are quite different, and, therefore, a detailed study is required for conventional.

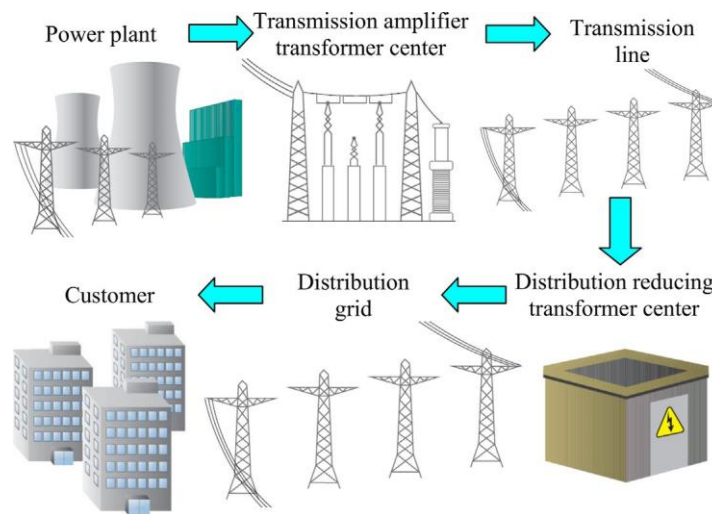


Fig. 8.1. Conventional electricity grid transmission structure.

Grids. It includes many steps for developing and expanding the conventional grid, maintenance activities, integration of distributed production and storage, and the development of a comprehensive two-way communication system. Fig. 8.2 is given to show the smart grid electricity transmission structure.

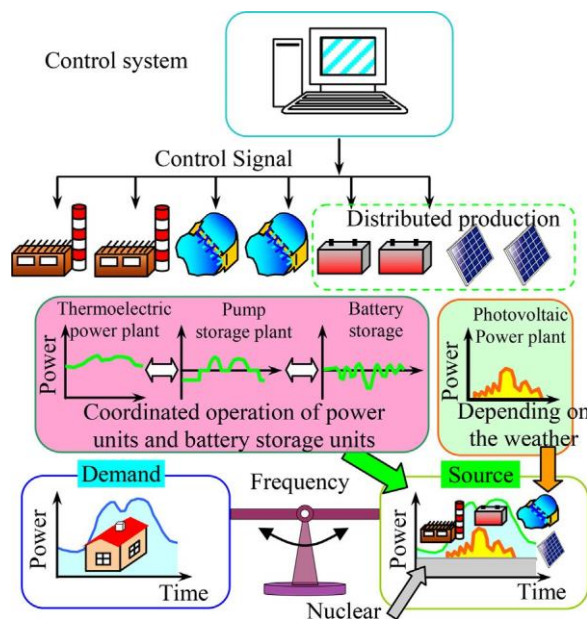


Fig. 8.2. Smart grid electricity transmission structure.

With a smart grid structure, electrical energy should be presented to all

consumers in a sufficient, continuous, quality, low-cost, and environment-conscious method. Electricity transmission and distribution services should be provided in a quality and should be sufficient to meet consumer satisfaction. Necessary measures should be taken considering the activities of climate change and environmental impacts in all areas of the sector. Minimizing losses and increasing efficiency in electrical energy, production, transmission, distribution, and use are an important issue for smart grid structure. In order to strengthen the smart grid structure, energy resource diversity should be increased and renewable energy sources should be used at the maximum level.

A smart grid is selective and it can also enable or disable the energy sources needed. Different power generation units can communicate with each other within the smart grid structure. By controlling all the powers in the system, power flow can be directed as necessary. A smart grid analyzes present situations, creates estimates and measures, and provides ease of operation/maintenance. In addition, its smart grid structure provides superior power quality, reliability, and efficiency. In the case of smart grid, many arrangements are needed in the process from energy production to its use within the framework of the objectives of ensuring energy supply security, reducing the risks rising from external dependence, increasing the effectiveness of combating climate change, and protecting the environment. With the smart grid structure, technical losses are minimized in electricity production, transmission, and the prevention of illegal use in distribution. In addition, end-user satisfaction can be increased by making regulations regarding demand-side management.

The smart grid is a concept that forms the future of electrical system and includes technology components from many different disciplines. These components are high-level energy management, transmission system, monitoring and control system, digital control technology, smart distribution system, information technology-based energy services, distributed energy generation systems, and microgrid structures. Table 8.1 presents the features of the smart grid structure and the conventional electricity grid.

There are some factors in the transition process of the electricity grid to the modernization phase. Political and legal factors especially with government regulations are of great importance in the development of smart grids. The structure to be revealed within the scope of the smart grid will reveal new job opportunities and business models. In terms of consumer satisfaction, service

quality, and sustainability, the issue of ensuring energy reliability and security at all times is an important factor that requires smart grids. With the support of adding renewable and distributed production to the grid, significant breakthroughs are needed in terms of environmental sustainability within the scope of the smart grid.

Table 8.1

Comparison of conventional and smart grid structures.

Conventional grid structure	Smart grid structure
Consumers do not have enough options to reduce energy consumption and costs	Detailed price information is available; many programs, prices, and payment terms are selected
Central production is used, and there is very limited distributed production and storage	Distributed production resources are also included in central production
There is a limited wholesale market for the integration of new technological developments	The development of new electricity markets, taking into account the technological developments and different production options, is provided
It focuses more on interruptions than on power quality	Power quality is a priority for smart grid
There is limited artificial intelligence and automatic control grid structure	In grid applications, efficiency increases with artificial intelligence in energy management
It focuses on the protection of assets after failure	It takes precautions to prevent malfunction before the malfunction minimizes the effects on malfunctions and ensuring operational continuity
It is very weak against natural disasters and other dangers	In situations such as natural disasters and attacks, the system quickly recovers and continues to operate

8.2. Microgrid structures

One of the most important subcomponents that make up the smart grid is the microgrid structure. Different definitions can be introduced to the concept of microgrid. Microgrid with smart energy management unit generates its own energy in local energy production units and ensures that the loads are fed in a balanced and controlled manner. In addition, the energy systems of commercial/residential buildings that can be the grid connected and

independent from grid can also be defined as microgrid. Moreover, a regional distribution system that can control the production and consumption units with smart systems and provide a balanced operation when the connection to the main electricity grid is lost can be defined as a microgrid. An example of a microgrid structure is given in Fig. 8.3.

The microgrid consists of on-site power generation (distributed generation), local loads, and electrical breaker. Smart microgrid can be defined as the electricity grid that makes electricity generation, distribution, and adjustment of the electricity flow given to local electrical consumers in a smarter way. The advantages of the smart microgrid can be expressed as increased reliability, increased

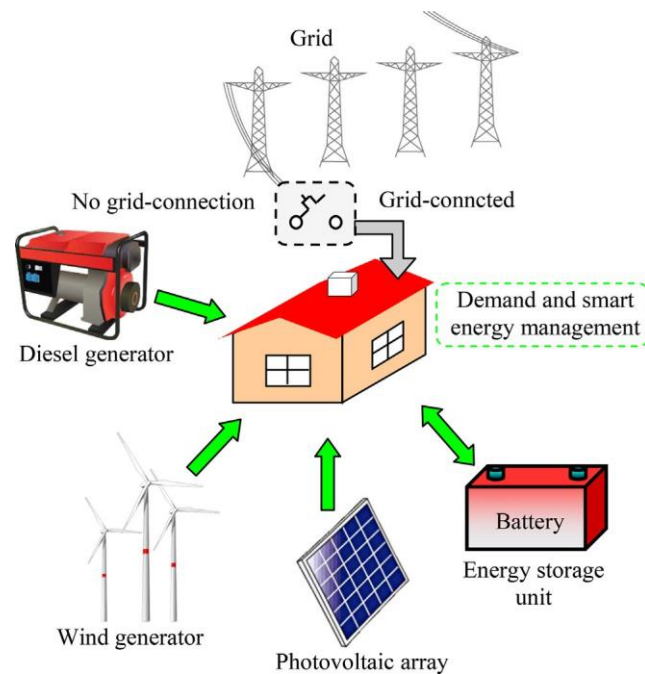


Fig. 8.3. Microgrid electricity transmission structure.

Efficiency, increased sustainability, and gain. Thus the integration of distributed energy sources into the grid becomes easier, reducing energy costs/interruptions and improving power quality. The most important problems in the micro grids structure are the synchronization of distributed energy generation sources, starting currents drawn by loads, and three-phase imbalance problems. In a smart grid structure the number of resources in the system can be increased by synchronizing energy storage systems with distributed energy generation resources. In the smart grid, fluctuations in electricity production and consumption can easily be met with the help of the

energy storage unit connected to the system. With the distributed generation structure in the system, the loads on the demand side are not affected by voltage fluctuation and drop, three-phase imbalance, and voltage harmonics. During a long energy interruption, if the power consumption is more than production, the micro grids structure ensures the continuity of the energy by disabling some loads to continue feeding important loads. When a load in the system is temporarily increased excessively, the unit feeding the load can meet the electrical power via an additional power line. Since the micro grids structure consists of too many units, a classification is needed. Therefore micro grids structures are classified as residential type, distribution plant, and commercial, industrial, and remote settlement micro grids. Electrical energy production and consumption units can be controlled in residential micro grids thanks to smart applications. Smart home systems with this type of energy management unit are in the development process. The local production units in the micro grids, energy storage units, and loads are connected to the local distribution grid with a controllable interface in smart homes. The residential micro grids structure evaluates the factors such as energy usage time, prices, or tariff information. Factors such as the duration of use, energy prices or tariff information are evaluated in the residential micro grid structure. The amount of energy produced in the local generation unit, the amount of energy in the energy storage unit or the amount of energy that can be drawn from the grid are calculated. Among these units, choices are made to provide the most economical and reliable operation.

The distribution plant may also be considered as a partial part of the micro grids systems for the residential area or for an industrial zone. Possible problems in the distribution network can be prevented by the proper operation of local distributed generation systems (wind turbines, biogas plants, energy storage applications, etc). Against loads in such micro grids. Quality energy can be provided to consumers by operating certain parts of the distribution grid as micro grids, operating these parts in island mode in the case of maintenance or failure.

The micro grids structure can provide energy reliability especially for consumers with critical and sensitive loads in commercial and industrial micro grids. Especially in large consumption units such as universities, hospitals, schools, and shopping centers, micro grids applications can be used to fully control all energy consumption units in their systems. In this way, energy

savings as well as economic benefits can be achieved with various applications in a fully controlled system. Micro grids may be suitable for remote location areas with poor or no connection to the grids. In such places, it should be ensured that they utilize local energy sources as much as possible and be loaded into the mains as little as possible. For such residential areas, micro grids application can be very suitable for the integration of renewable local distributed generation facilities and the entire system under control.

Dynamic control in micro grids

The most important feature of a micro grids is that it can be separated from the main grid very quickly, when necessary. Another feature is that it can be put into operation in island mode and, if necessary, can be switched from the island mode back to the grid. In this case the micro grids should be able to provide the energy needs of the loads dynamically without the need for information from the loads. This situation requires using energy storage units in the system. In terms of control method, different control strategies should be applied in the case of grid-connected state and no grid-connected situations. In the grid-connected state the grid provides reference values for voltage and frequency. However, when it is switched from the grid to the independent state, the micro grids must establish the voltage and frequency reference values as well as it must ensure the load balance and production balance. In this way the need for two different operating modes and a different control strategy for each different operating mode are the main challenges of switching modes. The main concern is the transition from island operating mode to grid-connected mode, because the reference values used in island mode differ from those used in grid-connected mode.

An superior control unit is required to decide the operating modes and to produce reference values for the specified operating mode. The signals are received from the connection point of the system to the grid and the networked mode or island mode, and thus, the operating modes are decided. The micro grids operates as a power generator in grid-connected operation. There are peak clipping, valley filling, and energy efficiency for grid-connected mode. These statuses are valid only for mains-connected operation mode. Load shifting is essential in island mode operation independent of the grid. Sample graphics for dynamic load control applications are given in Fig. 8.4.

Peak clipping is the reduction of peak loads in the system. It is one of the

classic ways of load control management. Peak clipping mode is user-preferential and user-defined values. The user defines a demand load value that must be fed continuously from the grid and in cases where an excess load exceeds this load value, these excess loads are not drawn from the grid, but from renewable sources or stored energy. Valley filling is the second classic form of load control management. Valley filling involves creating loads for nonpeak time periods. This is especially used to increase the load factor (rate of base load to peak load) over a period of time.

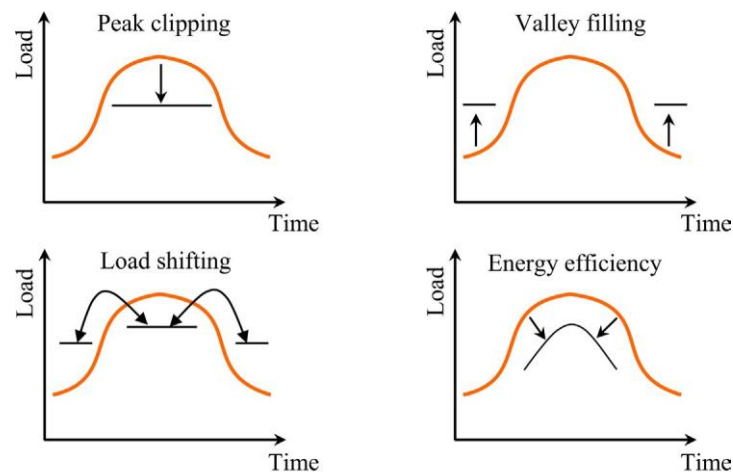


Fig. 8.4. Dynamic load control applications.

Load shifting is the final form of load control management. This approach involves shifting loads from peak to nonpeak hours. In this way the production side arrangements required to meet the peak demand can be prevented.

Energy efficiency can be evaluated within the scope of load control management. It is a changing situation that usually occurs according to the technological or usage features of the device used. The unit spent for a service without reducing the comfort conditions of the consumer is the reduction of energy and thus the downward shift of the load pattern is carried out. Consumers and suppliers can act independently to change the way they load. However, the demand-side interaction is aimed at a bilateral gain between suppliers and consumers.

Distributed production grid structures

Distributed generation grid structures have become a part of smart and micro grids. The developments in the electric power system in recent years encourage energy production units and energy storage units connected to the

power system from the distribution level. Taken together, these applications are defined as distributed generation units, although new technologies that can be applied as distributed generation units are being marketed and applied commercially. The various studies are continuing to integrate these systems into the grid, to use them more efficiently, and to reduce costs. Examples of distributed generation units are micro turbines, fuel cells, photovoltaic (PV) systems, wind turbines, diesel generators, and gas turbine systems. With these technological developments, the electric power system is undergoing a complete change. The goal of this change is that the highest utilization of clean and renewable energy potential is to provide consumers with more reliable and quality energy.

Grid-connected distributed solar systems

Distributed generation systems with grid connection are seen as indispensable components of increasing importance within the system as an energy source. However, the expansion of PV systems is a major challenge for grid designers, operators, and engineers working in this field. This difficulty can be summarized as the negative power quality effects of PV systems due to their widespread use in the grid that they are connected with due to continuously variable and intermittent power output. In addition, the disadvantage is that the PV system output power and demand power peaks do not match and can lead to inefficient use, which is a problem to be solved. To solve these problems, grid-connected energy storage applications located close to PV systems are very successful.

The reason why the output power is unstable in the PV power generation system is natural conditions such as cloud transitions, air temperature, and seasonal changes. The large and sudden drops in PV system output power can be seen with such effects. These major power changes are important problems for grid operators. Partial cloud transitions, especially visible in summer, cause a sharp shadow transition and can cause a power fluctuation of approximately 25 % in PV panels, which changes over a few seconds. These changes are very difficult to predict. Such sudden drops in the PV system power output must be filled with a supporting system. It is also known that PV systems can only produce power from sunrise to sunlight and reach peak values of power generation, especially at noon hours when the sun reaches a right angle. The daily load requirement of a house and the power graph produced by the PV

system are given as examples in Fig. 8.5. When compared with the load demand curve, it is seen that demand values are low in this range and PV power generation is not reachable in the evening hours when demand values reach peak values. In this case, there is a need to provide drivability in order to match the PV system power generation and the demand graph. In balancing such daily power changes, it can be seen that PV solar systems are supported by wind energy systems.

Another remarkable risk arising from the PV systems, especially in the distribution systems, which dominate the house loads, is that the generation values of the small power PV systems scattered in the distribution grid exceed the demand values in that region and have a serious impact on the voltage level in the region. Another problem that occurs in this case is called reverse power flow. In this case, redundant PV power generation in the distribution region is transferred to the grid and current flows from the secondary of the distribution transformer to the primary. Conventional distribution transformers are designed as a unidirectional current transition, so they are not designed for a bidirectional power flow. With the decrease in PV system installation costs, this problem is expected to gain importance in the coming years.

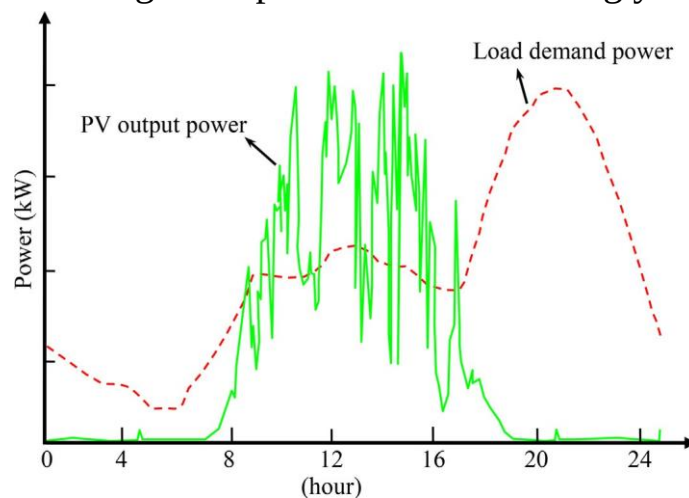


Fig. 8.5. Daily power generation graph of a PV system.

8.3. Energy storage application in distributed solar systems

Energy storage system is very important for a smart microgrid structure. The energy storage system used to ensure the proper functioning of the loads in the grid can also improve the power quality. Depending on the climatic conditions, the output power fluctuation of solar energy and wind energy,

output power of which varies, can be coped with energy storage applications. The concept of smart micro grids based on renewable energy is a good way to reduce the use of resources and fossil fuel consumption. The use of energy storage applications becomes mandatory by using micro grids to provide quality power to loads. There are two operating modes: grid-connected and isolated/island modes in micro grids. The main responsibility of the energy storage unit during the isolated/island mode operation is to ensure the energy balance. The purpose of the grid-connected mode is to prevent intermittent and load fluctuation of renewable energy sources from affecting the grid. In a micro grids that uses renewable power with uniform energy storage, not all of these functions can be performed effectively. Renewable energy sources such as PV require the use of high energy density storage. At the same time, sudden changes in the load require high power density storage.

In the PV system integration the energy storage application can be connected directly to the grid as a whole with the PV system as well as to the central or distributed independent energy storage units in the regions where the PV system installations are concentrated. In all of these options, grid risks originating from the PV system can be prevented.

First of all, it is possible to obtain a smoother character of the PV system power output graphic with the energy storage. Power over certain limits can be stored and discharged for power values below certain limits. Thus a smoother power curve can be reached within a certain range at the output of the PV system and storage unit. The negative effects of the sudden fluctuating power structure on the grid can be suppressed. Fig. 1.7 is given the positive effect of the system on the grid that is given by using the PV energy production system and the energy storage system together.

Energy is stored when demand values are low by using PV energy production system and energy storage unit together. Stored energy is offered for consumption in the range where there is no PV generation and the load demand reaches peak values. The most economical operation is provided on the consumer side, while the loading rate is reduced on the grid side with such an application. If the energy storage system has power electronics or power converter structure, the energy storage unit can also be operated with voltage and reactive power regulation by controlling power quality.

PV energy systems have become an indispensable power source in the power systems of the future with their environment-friendly structures and

simple, maintenance-free, and cost-effective operation possibilities. However, as mentioned earlier, the increase in the prevalence of these systems in electrical grids poses serious risks. The necessity and efficiency of energy storage applications

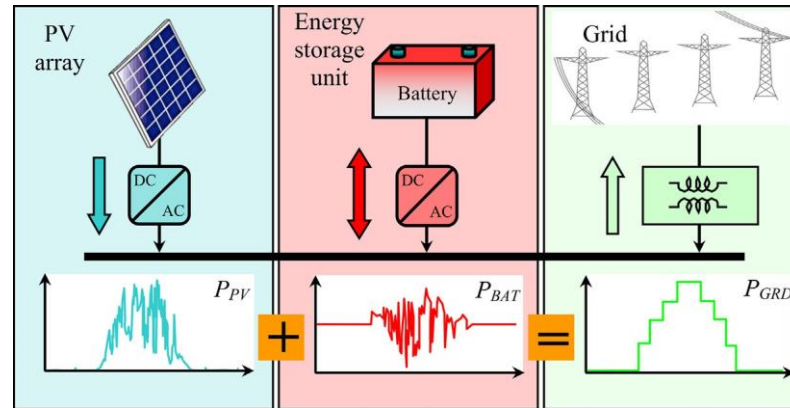


Fig. 8.6. Effect of PV and energy storage system on the grid.

Are remarkable in terms of solution applications. In the grid structure, different energy storage applications should be available to meet the needs in the most appropriate way. One of the most important key elements of the smart grids of the future is seen as energy storage applications. Costs are seen as the biggest obstacle to the spread of energy storage applications. If energy storage applications are integrated into small powerful residential PV system applications, access to these benefits will be achieved in a much more economical way, because, in such applications, costs such as wiring, communication, control system, power electronics devices, and labor are common for PV system and energy storage application. Fig. 8.6 is depicted effect of PV and energy storage system on the grid.

Energy storage systems must be controlled with energy management systems to ensure uninterrupted supplying of critical loads. Successful management of the microgrid is possible with suitable control and operation of storage systems. Electronically interconnected micro sources are advantageous in terms of maintenance of the grid without interruption. Energy storage systems support this situation and support micro sources in low-voltage transients, motor startups, and other short-term overload conditions, especially in island mode operation. Energy storage systems should be able to respond immediately to changes in load demand. Therefore they should be managed by local control units. Some energy storage sources, such as ultracapacitors, are

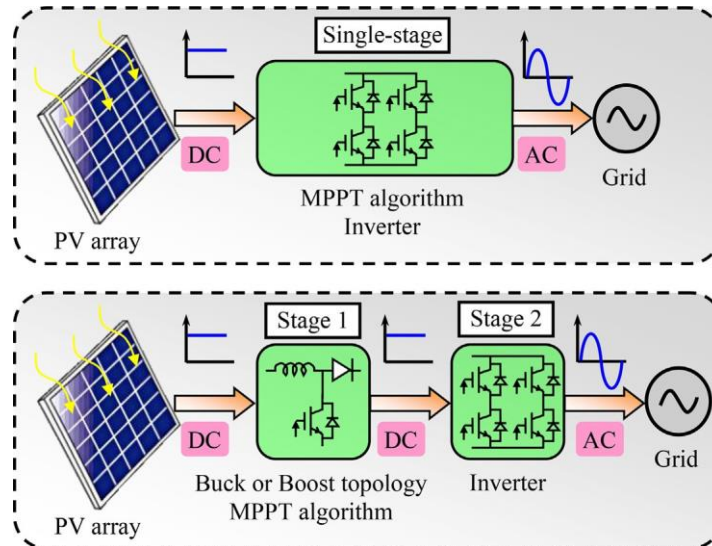
discharged in a short time, although they have high power density. Flywheels can provide energy for a long time, even if they have low power density.

8.4. Inverter structures in smart grids

In grid-connected systems, there are usually two or more converter stages. It may be necessary to increase or decrease this voltage level depending on the available PV array voltage. In the first stage, it usually includes a special.

Direct current (DC)/DC power converter to perform voltage level conversion and maximum power point tracking (MPPT) algorithm. The structure of the single-stage and dual-stage converter topology is given in Fig. 8.7. The disadvantages of the dual-stage system are less efficiency, larger size, and higher cost. For this reason a single-stage grid-connected structure is used that is common today because of its small size, low cost, high efficiency, and high reliability. Only DC/alternative current (AC) power converter is available in this system topology. Single-stage PV systems can be easily used for compact module and plug-and-play applications. DC/DC converter stage is not used in a single-stage structure. The MPPT takes place at the inverter power stage in single-stage grid-connected PV systems. Factors such as overall efficiency, reliability, and control complexity are important issues in grid-connected PV systems. There are cases of efficiency and reliability issues as the number of stages increases in the double-stage system. Therefore it is desirable to reduce the number of stages contained in such systems. There are two alternatives to achieve this: either to use a step-up transformer to the power converter output or to use a high-voltage PV array. The first option causes an increase in system dimensions (power density). The second option can increase the possibility of leakage current by reducing safety and parasitic capacitance. This situation leads to dangerous spots during the partial shading of the PV array. An ideal solution is to use an intermediate power converter, with only a single-stage low-voltage PV array. In this single-stage low-voltage PV array, time, maximum power is taken from the PV array, the voltage is increased, converted into a quality AC waveform, and at the same single-stage inverters must both transfer sinusoidal power to the grid and perform the MPPT algorithm. Single-stage grid-connected PV systems perform both cycles in single power conversion simultaneously. Thus the system topology is simplified. The MPPT method should be run at low speed to maintain system

stability. MPPT algorithm calculates the maximum power point of PV panels with voltage and current sensors. In order to prevent voltage sags events, monitoring is performed with a minimum step length to change the reference value of the power. It is quite difficult due to the nonlinear I–V characteristic



of PV array. The MPPT algorithm sets the reference current or voltage value that the PV panel should work with. One of the methods commonly used in gridconnected single-stage PV systems is perturb and observe technique. This technique determines the reference current and then provides a synchronous current to the grid. The reference voltage is used to calculate the grid reference current.

Fig. 8.7. Single-stage and dual-stage converter topology.

In other control methods, it gives accurate results when operating in the negative slope region of the PV array or in the voltage source region of the P–V characteristic. Based on these methods, the controller is designed in such a way that the reference voltage and reference mains current operate in reverse proportion in this region. The PV array continues this proportion as if it entered the current source region. When sudden weather change occurs, the system remains unstable and the control fails as the working point moves to the positive slope region. In addition, only the step size change can be made to prevent grid current disturbance.

Isolation and leakage currents in solar inverter structures

Isolation and safety are an important issue in PV systems without transformers. Small powerful PV single-phase systems are usually installed with a power capacity of 5–6 kW. While there is a DC source at the inverter input, there is AC power at the inverter output. Large powerful DC capacitors in single-phase systems reduce the reliability and long working life of the system. On the other hand, large capacitors are not needed in three-phase systems. The reliability and long-term operation of the system can be provided at a small cost. As for security, galvanic isolation transformers are used in PV systems. High-frequency transformer is used in DC/DC converter structures and low-frequency transformer is used in AC output. Adding a galvanic isolated transformer increases the cost and size of the system and reduces overall efficiency. A high-efficiency inverter can be made without including an isolation transformer. The transformerless structures are generally advantageous, when preferred. However, on the side of the solar panel parasitic capacitance, grounding safety issues occur. System grounding is done by connecting a capacitor between the PV panel terminals and the ground. A model with parasitic capacitance capacitors connected to a PV system is given in Fig. 8.8. Leakage and fault currents are grounded to ensure the reliability of the grid-connected PV system. Parasitic capacitance capacitor value is chosen depending on many factors such as PV panel and PV

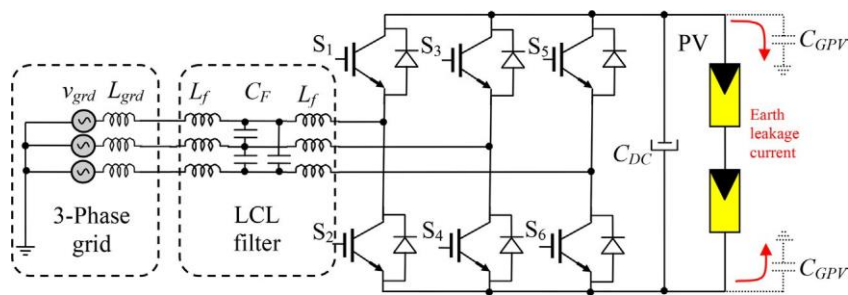


Fig. 8.8. Three-phase full-bridge inverter topology.

Model frame, cell surfaces, and distance between cells, weather conditions, and humidity/dust. The three-phase full-bridge inverter topology given in Fig. 8.8 is the simplest and most widely used structure for grid-connected PV systems. A galvanically isolated system was installed between the PV array and the AC grid. If no current flows into the parasitic capacitance capacitors,

the grid current is in a smooth sinusoidal curve. Under the same conditions, if there is no galvanic isolation between the PV array and the AC grid, leakage current flows to the ground. The same grid current draws a larger oscillating sinusoidal curve than the previous current curve. Also in this topology structure, it contains highfrequency components at common-mode voltage. Due to the high switching frequency between the DC buses, the leakage current value is also very high. These values go beyond the grid-connected PV system standards.

The three-phase full-bridge voltage-sourced inverter structure with split connection is given in Fig. 8.9. Unlike other topology structures, capacitors and PV array are connected in a similar way to the input side. In this structure, PV array and capacitors are divided into two equal parts. Their midpoints are connected to the neutral point of the grid. This topology is equivalent to three independent single-phase half-bridge inverters. In this structure, current control is used to control the switches. Two strategies are used for pulse width modulation (PWM). The first is to use a single triangular carrier signal for all three phases. The second is switching using three triangular signals with a 120° difference. The purpose of this method is to eliminate switching harmonics in the grid neutral current. By using triangular signals for PWM, the common-mode voltage for the three phases can be reduced.

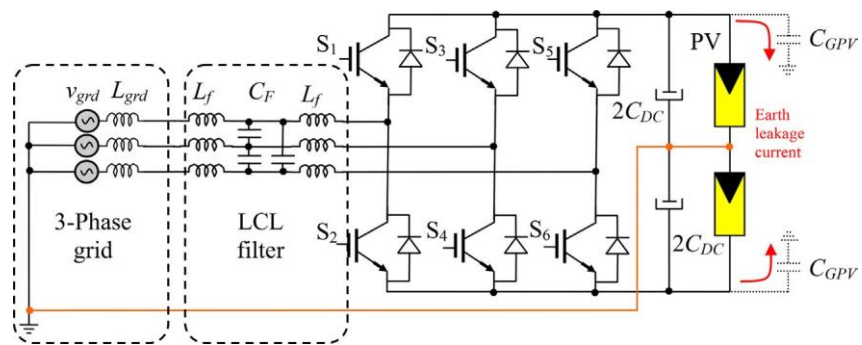


Fig. 8.9. Three-phase full-bridge inverter topology with split capacitor

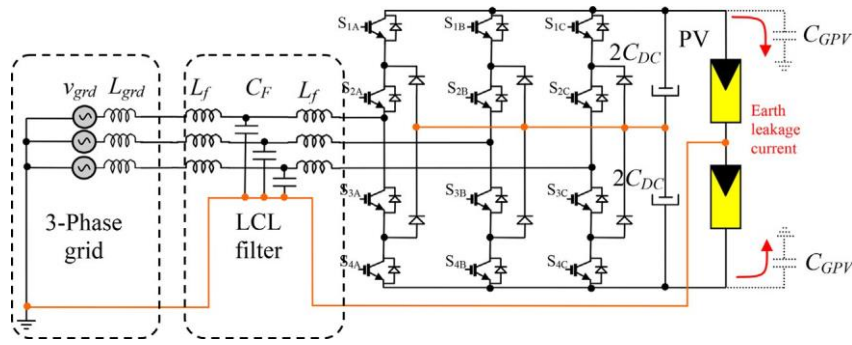


Fig. 8.10. Three-phase neutral-point-clamped inverter topology.

The DC bus voltage fluctuations in this inverter structure are much smaller, as they keep the neutral at zero potential. In this topology, few fluctuations occur in the ground and DC bus voltage and leakage current is greatly reduced. These values are within the grid-connected PV system standards and have a reliable structure. The three-phase inverter structure with three-phase neutral point clamped is given in Fig. 8.10. This structure is interesting for PV and other renewable applications, compared to six-switch full-bridge inverters with some important advantages. These advantages are as follows:

- Since the switches are connected in series and the voltage is split, the voltage stress on the switches decreases.
- Since the output phase voltage has two levels, the voltage at the output contains lower harmonics.
- Output filter size decreases because of low dv/dt ratio.
- Since low switching voltage is used, switching losses decrease and efficiency increases.

There are three separate current controllers for each phase and the output current is always synchronized with its own phase voltage. In this topology structure, it is more convenient to use a transformerless PV inverter as there is no voltage fluctuation and earth leakage between the PV panel terminals. Since these values are among the standards, it becomes a suitable solution for PV systems.

When examined in terms of power converters, six switching elements and six reverse diodes are used in the three-phase neutral-point-clamped inverter structure. In this case, only half of the voltage value of the switching elements is needed compared to the other two topologies. Since the midpoint of the capacitors is connected to the neutral line, an extra function is required to control the voltage imbalance. If the load is directly connected to the capacitors, it will cause voltage unbalance between the upper and the lower

capacitors as the load current will be drawn from the capacitors.

Earth leakage is one of the important issues for transformerless PV systems. Leakage current is very high due to the three-phase full-bridge inverter structure having high common-mode voltage. On the contrary, there is almost no voltage fluctuation in the three-phase neutral-point-clamped inverter and three-phase full-bridge inverter with split capacitor structure. Since there is a small voltage fluctuation, the earth leakage current to be formed is more advantageous as it complies with the standards. If three-phase full-bridge inverter topology is used, lower fluctuation occurs in the grid current with galvanic isolation. In fact, in the structure with transformer, the triple harmonics of the grid current are canceled. The grid current is subjected to subharmonics within limit values.

The fluctuation in the grid current is in the lowest three-phase full-bridge inverter with split capacitor, then in the three-phase neutral-point-clamped inverter, and the highest in the three-phase full-bridge inverter topology. Different inductance-capacitance-inductance (LCL) filters must be selected for each topology to comply with the IEEE 929 standard. When the three-phase neutral-point-clamped inverter structure is used, the filter size is 20 % smaller than the three-phase full-bridge inverter structure.

With a high efficiency of up to 98 %, three-phase neutral-point-clamped inverter structure becomes the most effective topology for the transformerless PV inverter. Table 8.2 presents the comparison of these topology structures, switching number, voltage stress on switches, number of diodes, voltage unbalance control, common-mode voltage, earth leakage current, transformer requirement, grid unbalance effect, neutral leakage current effect, and LCL filter size.

Table 8.2

Comparison of inverter topology structures.

Inverter topology	Three-phase full bridge	With split capacitor	Neutral point clamped
Switching number	6	6	12
Voltage stress on switches	V_{DC}	V_{DC}	$V_{DC}/2$
Diode number	6	6	12
Voltage unbalance control	No	Yes	Yes
Common-mode voltage	$\pm V_{DC}$	$\pm 1 \% V_{DC}$	$\pm 1 \% V_{DC}$
Earth leakage current	High	Low	Low
Transformer requirement	Required	No required	No required

Grid unbalance effect	Low	No	No
Neutral leakage current effect	No neutral line	High	High
LCL filter size (per unit)	1	0.87	0.80

8.5. Grid-connected three-phase inverter structures in smart grids

The transfer of energy obtained from the PV panels to the grid is provided by distributed power generation systems. At the output of the solar panels, the DC voltage must be converted to AC voltage in order to energize the grid. This conversion is carried out with the inverter power unit. Three-phase inverters are used in high-power applications. While energy is being transferred to the grid, it is requested that the energy produced by the inverter be of high quality in order not to create a disruptive effect on the grid. Three-phase currents produced at the inverter output should be close to sinusoidal for high energy quality. The inverter should also work synchronously with the grid. Therefore the current control of the inverter must be done properly. The inverter must have high power density, high efficiency, low cost, and simple circuit structure.

The grid-connected inverter must synchronize with the grid and produce currents in the same phase in order to realize the power transmission. The harmonic contents of these currents should be low. According to the IEEE 519 harmonic standard, the currents transferred to the grid must have a total harmonic content less than 5 %. According to the EN 50160 standard, voltage harmonics should be maximum 8 %, voltage imbalance maximum 3 %, voltage amplitude maximum ± 10 %, and frequency value change should be maximum ± 1 %.

Three-phase voltage supply inverters. Three-phase inverters are used to generate AC output voltages from the voltage generated from the PV panel. A standard three-phase voltage-fed inverter structure is given in Fig. 8.11. The PV voltage is generated from the AC voltage using the S 1–S6 switching elements. Each switching element in the circuit remains in transmission for 180° . After one of the switching elements in the high-side arm enters the cut, the corresponding switching element in the low-side arm is transmitted after the dead time value. Thus two switching elements in the same phase are prevented from being transmitted simultaneously.

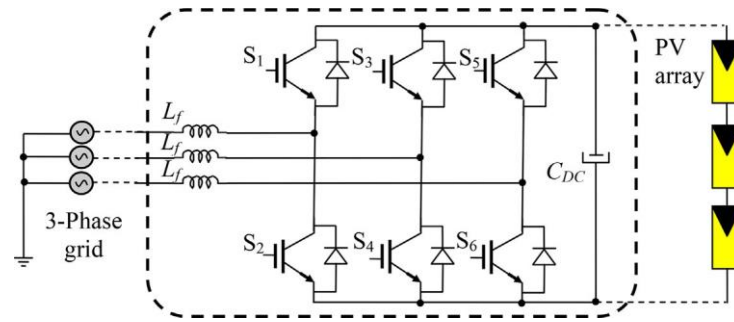


Fig. 8.11. Circuit diagram of the three-phase voltage-fed inverter

Modulation methods in three-phase voltage fed inverters

PWM is a method in which voltage pulses are produced by properly switching semiconductor power elements for the desired output frequency and voltage. A typical modulator generates an average voltage value equal to the reference voltage within the PWM period. Considering that the PWM period is too short, the reference voltage gives the basic component of the switched pulse sample. Among the numerous methods used to generate the output voltage, the main are sinusoidal PWM, hysteresis band PWM, and space vector PWM methods. The sinusoidal PWM and hysteresis band PWM methods can be performed using analog methods, while other methods require the use of microprocessors or digital signal processors.

In the sinusoidal PWM method, PWM signals are generated as a result of a comparison of a high-frequency triangular carrier wave with a sinusoidal modulation signal. This control method is frequently used in industrial applications. The frequency of the modulation signal determines the frequency of the output voltage and the peak value modulation index. The modulation index changes the effective value of the output voltage. As the modulation index increases, the inverter output voltage also increases and the index value gets the largest value of 1. The carrier wave at a high frequency, according to the modulation signal, determines the switching frequency of the inverter. The output harmonics produced occur in the form of switching frequency and its multiples.

To obtain the modulation signal, first, the current measured from the reference current is subtracted and current error is obtained. This current error is given to the proportional integral controller and the reference voltage is obtained at the controller output. This is done separately for each phase. Three-phase switching signals are generated by comparing the obtained reference

voltages with the carrier wave. In Fig. 8.12 the inverter output voltage produced for one phase is given as a result of the comparison between the carrier wave and the modulation signal.

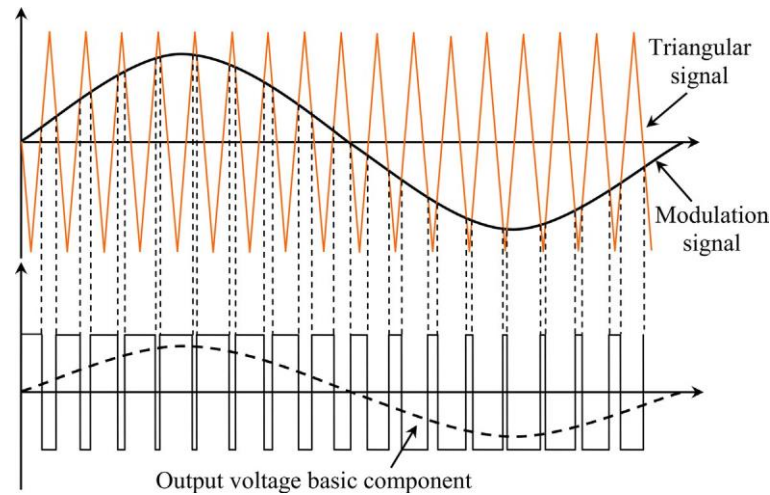


Fig. 8.12. Sinusoidal pulse width modulation.

Hysteresis current control method is a preferred control method for ease of application. Besides its fast dynamic response and natural current protection features, it is not affected by changes in system parameters. However, in constant band current control, the switching frequency of the inverter is variable depending on the voltage difference between the inverter output and the grid. Since the difference between the inverter output voltage and the grid voltage is high in the regions close to the zero crossing of the grid, the switching frequency increases and decreases toward the peak values of the grid voltage. This variable switching frequency complicates the input filter design. In order to control the current in the defined band, the input sampling should also be done quickly. The block diagram of the hysteresis current control method is given in Fig. 8.13. In this control method, currents for each phase are obtained by comparing the phase currents measured at the inverter output with the reference phase currents. This current error is applied to the hysteresis controller and its signals are obtained.

The current of each phase in the inverter is tried to be kept within the band defined by the current error as given in Fig. 8.14 by the hysteresis controller. The inverter output currents move in the band as the current error remains in the band. Since the current measured when the current error reaches the upper

limit of the band, the upper limit switch of the related phase is transmitted to increase the current, since the current reaches the lower limit of the band. With the increasing current the error starts to decrease and continues to increase until the upper band is reached. When the current reaches the upper band, the current error reaches the lower band and the upper switch is inserted into the sector and a signal is sent to the lower switch. Thus the inverter output current starts to decrease. This process repeats during each switching period and the output current is produced to move within the specified band.

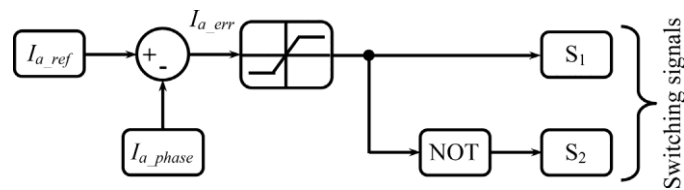


Fig. 8.13. Hysteresis current control method block diagram

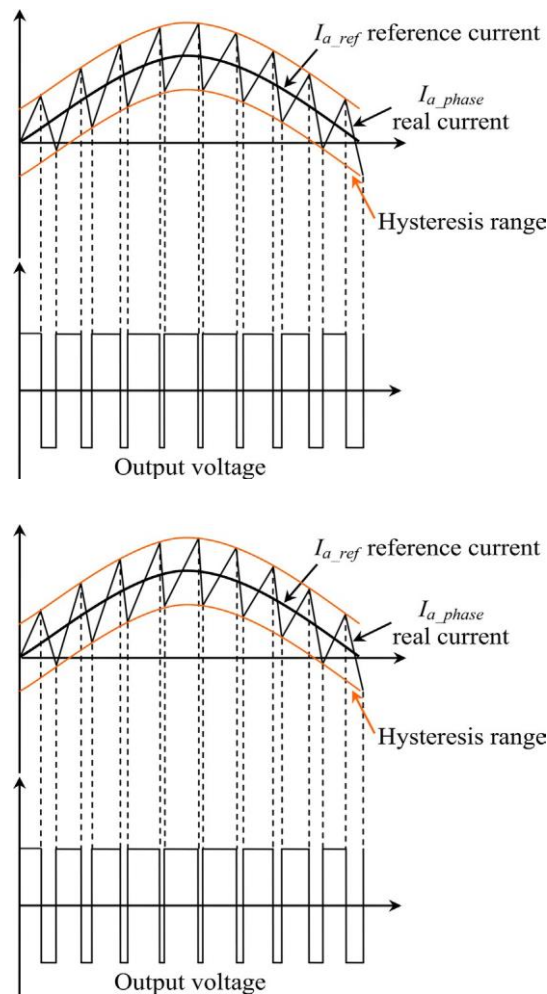


Fig. 8.14. Hysteresis current control PWM generation principle.

Space vector PWM method has found a wide application in recent years

with features such as no need for reference, sinusoidal input, lower harmonic content, and wider linear working area. According to the sinusoidal PWM method, DC input voltage is used 15 % more efficiently. This method is popular for its use in AC drives with a voltage-fed inverter structure. Since this control structure will allow a control system with a lower current to be used, the transmission losses in the voltage fed inverter can be reduced. In addition, the harmonic content and switching losses of the inverter output voltage and currents are reduced.

Distribution network must have a three-phase converter topology for low-voltage four-wire distributed network units. The distributed generation unit can also be used as an active power filter to improve the mains power quality. When an effective active power filter is desired, the converter structure must be a system that allows the neutral current to flow. There are four-wire topology, four-arm topology, and split-link capacitor converter topologies that allow this structure. The benchmarks can be classified as ease of control, circuit complexity, midpoint control, DC bus voltage utilization, and electromagnetic compatibility performance. The split-link capacitor converter topology offers the best option compared to the four-arm structure. For the same circuit complexity and the use of DC bus voltage control, split-link capacitor topology results in easy current control and less electromagnetic compatibility problems.

The choice of converter topology has a significant effect on its connection to the four-wire distribution grid. The neutral line can be achieved by adding a fourth arm to the converter (four-arm converter) or by connecting the midpoint of the split-link capacitors to the neutral line.

Classic three-phase, three-wire inverter topology is given in Fig. 8.15. Since the low-voltage distribution grid is a typical three-phase four-wire configuration, a converter transformer is used to connect to the grid. Since this transformer is heavy and expensive, it is not desired in many applications. In some cases the transformer can be used as part of the filter impedance. Another disadvantage is that the absence of a neutral line restricts the use of active power filters, since various filter methods require neutral current.

Instead of using Δ/Y converter transformer, neutral line can be provided with three-phase four-wire converter topology. The neutral line can be made by adding a fourth arm to the inverter structure or by adding two capacitors to the DC bus. Neutral wire will allow the use of active power filtering

techniques. The four-wire inverters are more preferred than three-wire ones.

The four-arm converter topology is given in Fig. 8.16. Two extra S_7 and S_8 switches are used to control the neutral line. In order to weaken the high

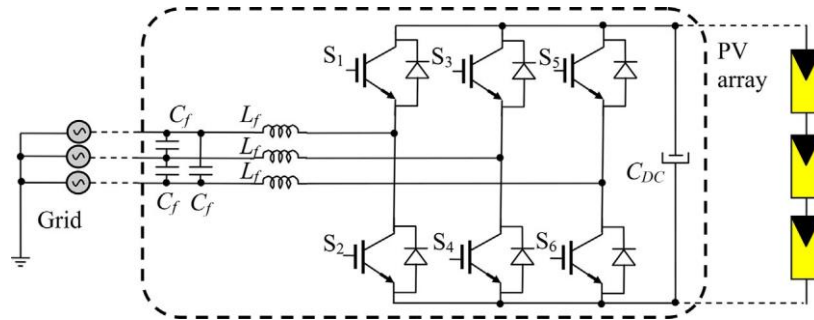


Fig. 8.15. Three-phase, three-wire inverter structure.

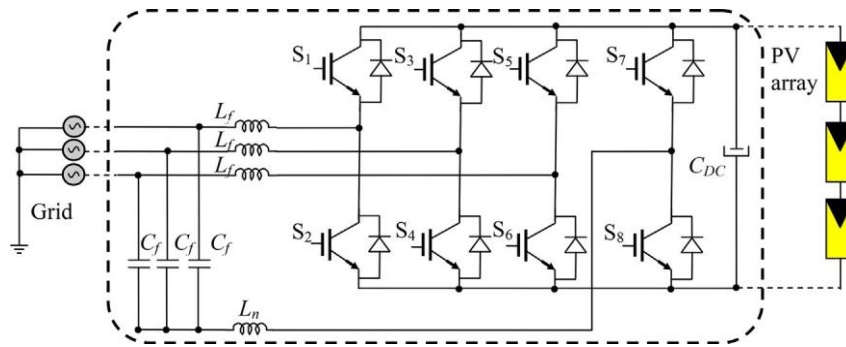


Fig. 8.16. Three-phase, four-arm, four-wire inverter structure.

Frequency currents due to the switching of the fourth arm, L_n choke coil must be connected to its neutral line. It is sufficient to connect a C_{DC} capacitor to prevent voltage fluctuations in the DC bus. There is a split-link capacitor, a four-wire inverter structure, in Fig. 8.17. This structure has fewer switching elements due to its simple topology structure compared to the four-arm inverter. The DC bus line is divided by $2C_{DC}$ capacitors. Since there is no switching at this point, there is no need to connect a choke coil to the neutral line. The split-link capacitor converter can be considered as a three-phase half bridge inverter, which can be controlled independently. The voltage unbalance of the DC bus capacitors is a known issue in the split-link capacitor converter topology. High voltage fluctuations due to neutral line currents are another problem. These voltage fluctuations should be reduced with capacitors.

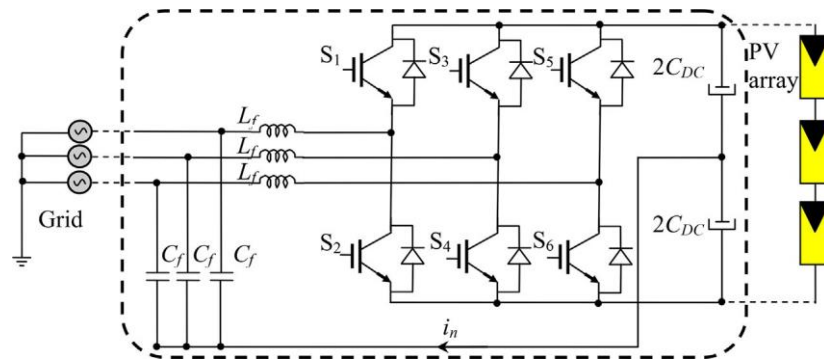


Fig. 8.17. Split-link capacitor, four-wire inverter structure.

A neutral line is preferred for programming distributed units with a secondary filter function. Δ/Y transformer is needed to obtain the neutral line in the three-wire converter structure. However, this situation becomes disadvantageous as it will increase the system size. Since distributed generation systems are widely used in the grid, these inverters can provide energy quality improvement when programmed with a secondary active parallel filter function. A neutral line is needed to use all this filtering potential. Therefore four-wire inverters offer an important advantage.

CONTROL QUESTIONS:

1. What is the basic operating structure of a traditional power grid?
2. Define the structure of a smart power grid.
3. What should be considered when analyzing and modernizing traditional grids?
4. What factors should be considered in power generation within a smart grid?
5. What are the advantages of the traditional power grid structure?
6. What are the advantages of the smart power grid structure?
7. What is the main function of a microgrid structure?
8. What components are included in a microgrid?
9. What are the advantages of smart microgrids?
10. How many operating modes exist in microgrids?

11. What is the effect of a photovoltaic (solar) system and energy storage system on the power grid?
12. What are the disadvantages of a two-stage system?
13. How is efficiency achieved in a two-stage system?
14. What are the advantages of three-phase inverters?
15. What is the structure of a three-phase, three-wire inverter?
16. What is the structure of a three-phase, four-leg, four-wire inverter?

Chapter IX

THE ROLE AND IMPORTANCE OF ENERGY STORAGE SYSTEMS IN SOLAR HYBRID APPLICATIONS

9.1. Energy storage systems in solar hybrid systems

Today, solar energy is one of the various energy sources, which is the subject of research as an alternative to fossil and nuclear fuels. Solar energy is rapidly becoming widespread due to its advantages such as being an infinite and widespread source, and it can easily be converted into electrical energy. Another important feature of solar energy systems is that it offers a wide range of power from a few watts (W) to megawatts (MW).

Photovoltaic (PV) panels produce direct current (DC). For this reason, all kinds of electrically powered loads can be fed directly or with the help of a converter from the PV panel. There are two types of application areas as the topology of the use of PV panel technology. These topologies can be examined under the heading of stand-alone (off-grid) and grid-connected systems. Off-grid systems are road lighting, small powerful autonomous applications, water pumping systems, signaling systems, and domestic applications located in remote areas. There are generally PV panels and battery energy storage system in off-grid systems. Energy from PV panels is used directly or stored in batteries. When the PV panel does not generate energy, the energy stored in the batteries is used.

Depending on the system structure, PV panels are operated as DC or alternating current with an inverter. Grid-connected systems work synchronously with the grid and transfer energy directly to the grid. Grid-connected systems may be small-powered examples of domestic applications. There may be large power plants to meet the energy needs of a particular region.

In this chapter, an exemplary solar hybrid system design has been realized. A grid-connected system was simulated by using PV panel array and inverter. PV panels were connected to the DC bus via a converter. PV panels were controlled by the perturb & observe algorithm using maximum power point tracing (MPPT) technique. Thus maximum power transfer is ensured from the PV panels to transfer maximum power to the grid and the load. A three-phase

fourarm inverter circuit was used as inverter structure. The reason for using the three-phase four-arm inverter structure is to allow feeding of unbalanced loads that may take place in the system. The inverter works synchronously with the grid and transfers the energy generated from the PV panels to the grid when there is no load.

Simulation of solar hybrid system

A MATLAB/Simulink block diagram of a simulation solar hybrid system is given in Fig. 9.1. The PV panel array, battery group, and three-phase grid were used in this simulation study. The MPPT technique and hysteresis current controller were used as control methods in solar hybrid system. In the simulation study, it is aimed at operating the grid-connected PV inverter structure at the maximum power point with MPPT technique. As the MPPT method, the perturb & observe algorithm was used, which is widely used

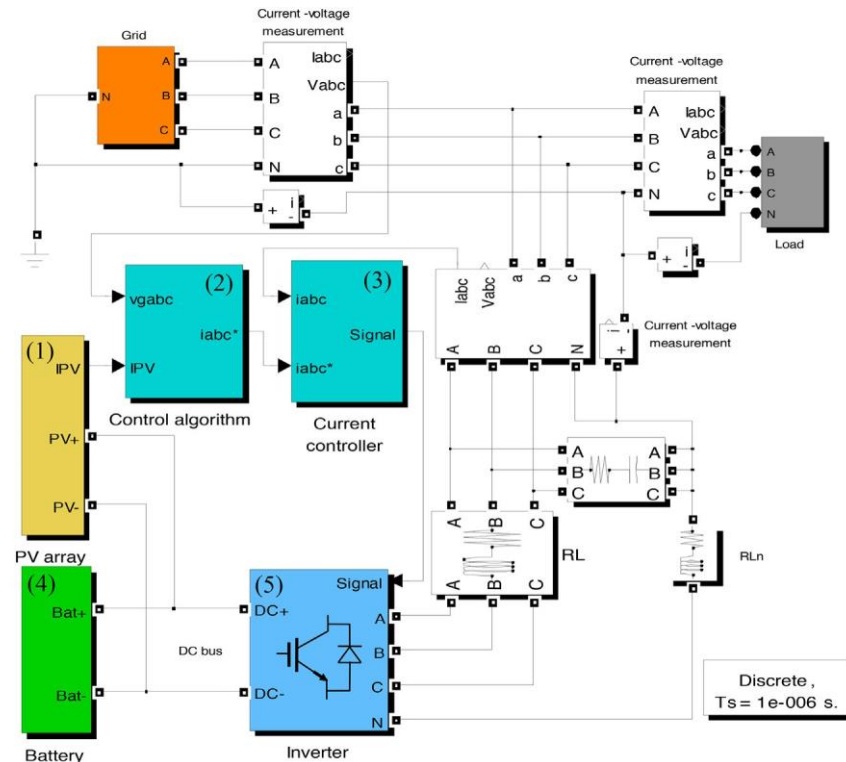


Fig. 9.1. MATLAB/Simulink block diagram of solar hybrid system.

In terms of applicability and cost, and also has a fast response time against changes in weather conditions. With this algorithm the system gets more efficient operation by taking maximum power from PV panels. The reference signal produced in the perturb & observe algorithm is processed in the current controller unit, and suitable operating signals are produced for the single-stage inverter.

For simulation of real weather conditions, working conditions under dynamic condition were examined. Thus the dynamic behavior of the perturb&observe algorithm on the system was observed. In the simulation study the weather condition was changed in 0.3 second of the system. The response time of the MPPT algorithm and the speed of capturing the maximum power point were determined.

PV panel inverter structure transfers energy synchronously depending on the grid. The inverter structure feeds the load group at the same time and transfers energy to the grid. The solar hybrid system can feed balanced loads with its neutral line structure as well as respond to single-phase and unbalanced loads. Under the same conditions the current and voltage of the inverter are examined by replacing the balanced load group connected to the system with the unbalanced load group. The six serial, two orders of parallel PV panel arms were created and 12 PV panels were simulated. In simulation, current, voltage, and power values were obtained by simulating PV panel array. System parameters used in simulation are given in Table 9.1.

Table 9.1

Solar hybrid system simulation parameters.

Parameters		Value
PV array	Open circuit voltage (V_{oc})	500 V
	Short circuit current (I_{ph})	2.5 A
	MPPT voltage (V_m)	410 V
	MPPT current (I_m)	2 A
Grid	Voltage (V_{gabc})	110 V _{rms} /phase-neutral
	Frequency (f)	50 Hz
	Impedance (R_g, L_g)	5 m Ω , 2 mH
Battery (lead–acid)	Voltage	48 V
	Current capacity	25 Ah
	Power capacity	1200 Wh
Load	Ohmic load	Single-/three-phase

PV array and perturb & observe control algorithm

In Fig. 9.1, block (1) contains PV panels and the perturb&observe control algorithm with MPPT method. A MATLAB/Simulink block diagram of PV panels and MPPT algorithm is given in Fig. 9.2. The perturb & observe method observes the PV panel voltage or current that fluctuates depending on the

weather conditions and changes the working points. It works by comparing the PV panel output power with the previous power value. PV panel operating voltage changes and if the power increases, the control system changes PV panel operates by pointing in this direction. Otherwise, the working point moves in the opposite direction. In the next cycle the algorithm continues in the same way.

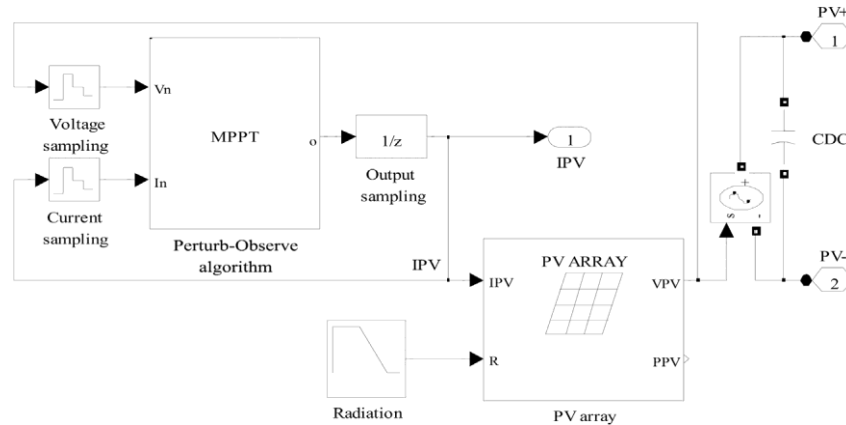


Fig 9.2. PV panel and perturb & observe algorithm block diagram.

The PV panel output power is constantly monitored in the deflection method. It is decided to decrease or increase the reference by establishing a relation between the movement of the control variable and the movement of the power. The program codes of the perturb & observe algorithm are given in Table 9.2.

Table 9.2

Program code of the MPPT algorithm.

Program code of the perturb&observe algorithm (MATLAB)
function o = MPPT_PO(vn,in)
persistent io;
persistent po;
persistent vo;
persistent iro;
persistent dsign;
if isempty(io)
io = 0;
po = 0;
vo = 0;
iro = 0.6;
dsign = 1;
end
delta = 0.02;
pn = vn*in;
if pn >= po
dsign = dsign;
else
dsign = 0-dsign;

end
irn = iro + dsign*delta;
vo = vn;
io = in;
po = pn;
iro = irn;
o = irn;
end

The input and output parameters of the system must be known in order to create the PV panel array in the simulation. Using Eq. (9.1) obtained from the electrical model of the PV panel, the PV panel array has simulated. In the PV panel model the input parameters are PV input current and radiation, and the output parameters are current and power. Switching signals are produced by processing the PV panel output current in the control unit. The PV panel power value is continuously operated at the maximum power point with the MPPT Algorithm according to the entered radiation value. The block diagram of the PV panel is given in Fig. 9.3.

$$I_{PV} = N_p I_{ph} - I_o \left[e^{\frac{q \left(\frac{V_d}{R_s} + \frac{I R_s}{R_p} \right)}{N_s K F T_{PV}}} - 1 \right] - \frac{N_p V_d I N_s}{R_p} \quad (9.1)$$

Battery model and bidirectional DC/DC converter model

In the battery simulation the lead–acid battery model in the MATLAB/Simulink library was used. This model simulates the battery’s voltage, capacity, and the battery state of charge (SOC) parameters. The battery-equivalent circuit used in the simulation is given in Fig. 9.4.

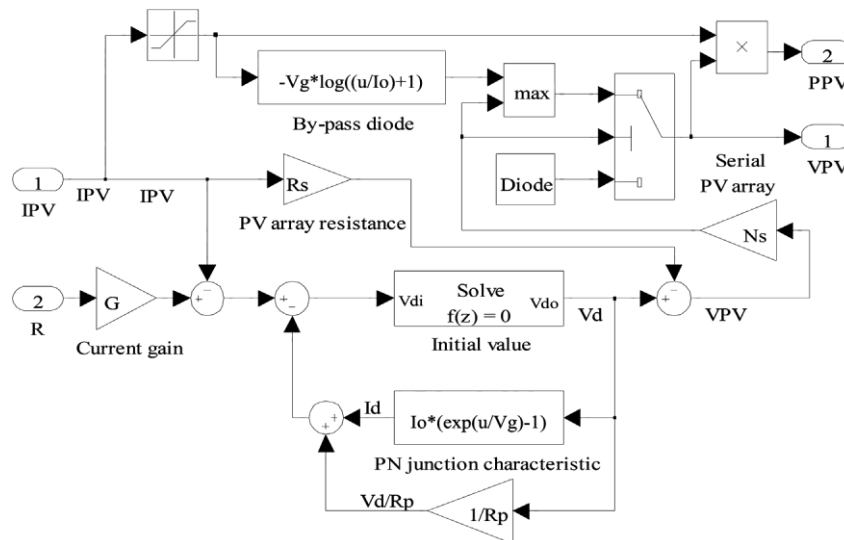


Fig. 9.3. PV panel block diagram.

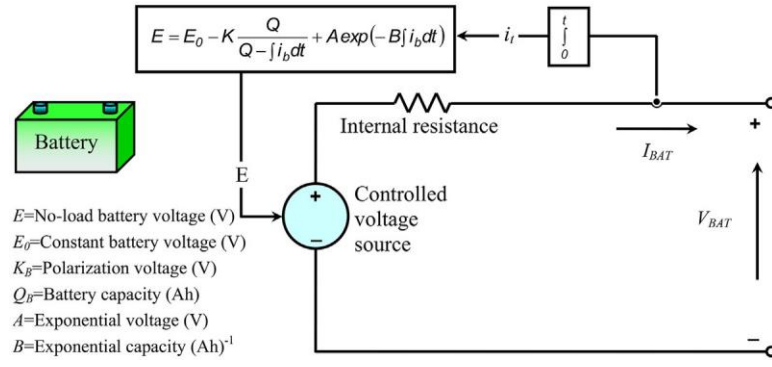


Fig. 9.4. Battery equivalent circuits.

A bidirectional DC/DC converter structure is used in the battery group, which is given in Fig. 9.5A. DC bus voltage is determined as 400 V in solar hybrid system. The voltage level of the battery group is 48 V, which is lower than the DC bus. It is not suitable to use only a buck or boost DC/DC converter in the system. For this purpose a bidirectional DC/DC converter is used, which can charge and discharge the battery. Increasing the voltage level of the battery group to 400 V and transferring energy to the DC bus is undertaken by the bidirectional DC/DC converter unit. In this case the SB 5 switch is passive as in Fig. 9.5 Band the pulse with modulation (PWM) signal is applied to the SB 6 switch. Likewise, it provides the battery group to be charged with the excess energy produced by the solar system. In charging mode the circuit reduces from 400 to –48 V. In this case, as in Fig. 9.5C, S_{B6} switch is inactive and PWM signal is applied to S_{B5} switch. In the bidirectional DC/DC converter structure, a coil, two semiconductor switching elements and capacitors are used.

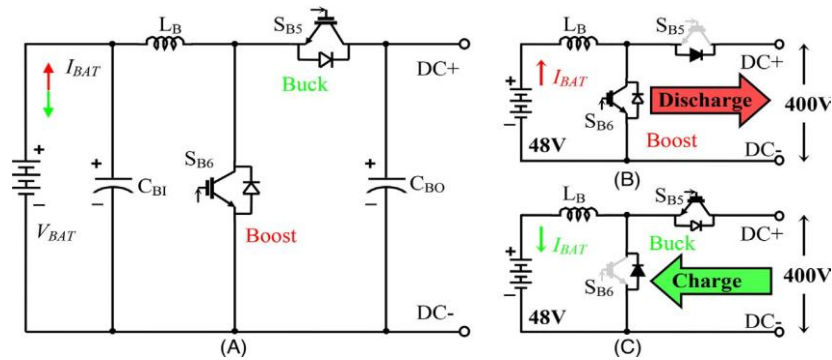


Fig. 9.5. Bidirectional DC/DC converter structure

9.2. Hysteresis band current controller and phase-locked loop (PLL)

The hysteresis band current controller compares the I_{abc}^* reference current calculated at the control unit with the i_{abc} current at the inverter output. As a

result of comparison, switching signals of the inverter are produced. Depending on the current fault, the inverter current is tried to be kept in the band defined by the hysteresis controller. A block diagram where inverter switching signals are generated using a hysteresis band current controller is given in Fig. 9.6.

One of the important issues in grid-connected PV power systems is grid synchronization. The angle of the grid voltage vector is determined by the synchronization algorithm used. Depending on this angle value, the switching elements of the inverter are triggered and MPPT control is performed in the system. Depending on the angle of the grid voltage vector, three-phase variables are reduced to the axis set rotating at synchronous speed.

Phase-locked loop (PLL) is used to give a pure sinusoidal current reference and to enable the inverter to operate at the unit power factor. PLL provides a synchronization of mains voltage and inverter output current. It is possible to determine the placement time and damping coefficients directly with the proportional integral (PI) control parameters of the PLL structure. PLL structure is also used to obtain amplitude and grid voltage frequency values and to monitor grid voltage. The angle produced is crucial for generating the reference I_{abc}^* signal in the dq0/abc transformation (park transformation). In Fig. 9.7, there is a park transformation and PLL control unit that processes the PV current value coming from the MPPT so that the three-phase inverter can transfer energy to the grid synchronously.

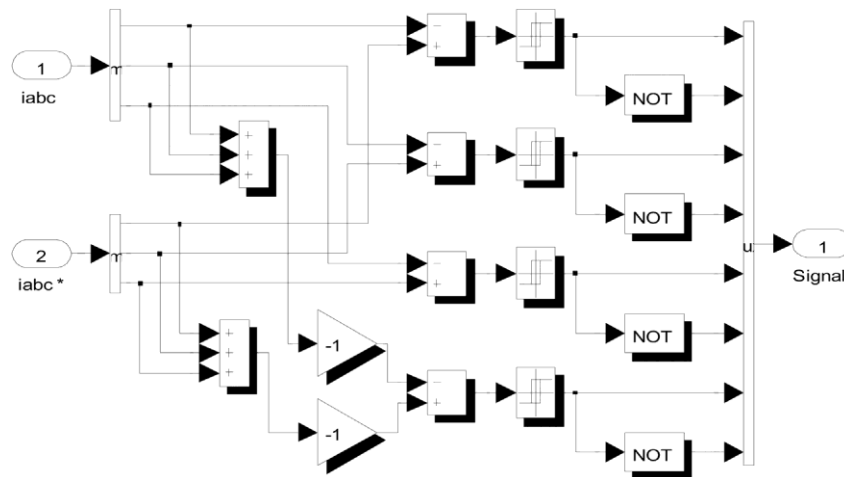


Fig. 9.6. Hysteresis band current controller block diagram.

Park transformation is used to reduce three-phase sizes to the axis set (dq0) rotating at synchronous speed. The same conversion is used to obtain three-

phase sizes with the DC component. Using the I_{PV} value generated in the MPPT method in the control algorithm block, I_{abc}^* reference signals are generated for the inverter to the current controller. With this transformation the rotating vector in the fixed axis tool takes a constant value. The d-axis component is equal to the amplitude of the three-phase magnitudes, while the q-axis component is zero in the balanced system. The dq-axis set rotates at the same speed as the variables in the three-phase system, and the angle produced in PLL is used for conversion. The resultant vector moves at a constant speed relative to the fixed axis set, while the dq remains constant relative to the axis set. Therefore the sizes in the dq-axis tool are DC. When it is desired to reduce the sizes in the three-phase system directly to the axis set rotating at synchronous speed, the park transformation given in Eq. (9.2) is used. The d-axis is I_{PV} , which is the PV array panel current, and the q-axis is 0.

$$\begin{bmatrix} I_{PVd} \\ IPVq \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta \cos\left(\theta - \frac{2\pi}{3}\right) \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin \theta - \sin\left(\theta - \frac{2\pi}{3}\right) - \sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} \quad (9.2)$$

9.3. Simulation results of solar hybrid system

The grid-connected PV system was operated according to two different situations, and PV current, voltage, power, grid voltage, current, inverter current, and load currents are examined. In the first case, it was examined that there is no battery energy storage unit in the system. In the case of no battery group the load power is supplied from the grid due to the PV panel power fluctuation. Since the PV output characteristic is instability, the power demand of the load from the grid is also fluctuation.

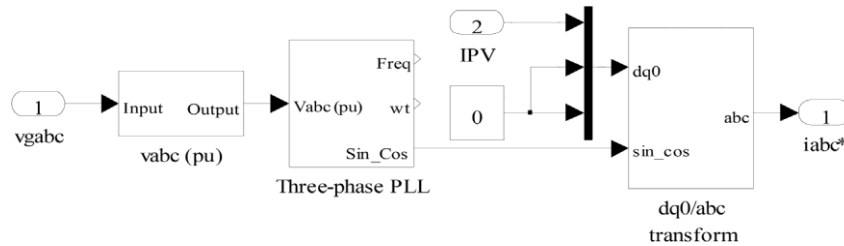


Fig. 9.7. PLL and park transform (dq0/abc) block diagram.

In the second case where battery energy storage unit is added to the PV solar system, the power fluctuation is covered by the energy storage unit. Battery energy storage unit discharges depend on the load power during power surge transitions. Thus there is no fluctuating power demand from the grid.

Through solar hybrid systems, there is a more stable energy demand from the grid. Power stresses on the grid are compensated by energy storage units.

Simulation results of control structures were obtained using MATLAB/Simulink Power System Toolbox software. Depending on these two different situations, the perturb & observe algorithm is shown to operate the response time and PV panels at the maximum power point. The PV inverter structure is operated as balanced and unbalanced load groups under the same radiation conditions. In the balanced state, there is a resistance of $75\ \Omega$ in each phase; in the case of unbalanced load, there is a resistance of $90\ \Omega$ in the C phase, and in A and B phases, it is $75\ \Omega$. A power flow diagram of solar system (not including battery) and balanced load status is given in Fig. 9.8.

The simulation works for a total of 0.5 second. The radiation is $1000\ \text{W/m}^2$ for 0.2 second, decreases to $500\ \text{W/m}^2$ for 0.4 second, and is operated at a radiation value of $500\ \text{W/m}^2$ in the range of 0.4–0.5 second. This radiation change can occur depending on the atmospheric conditions. The purpose is to see the fast response time of the MPPT algorithm and to examine how the system can react in the case of possible rapid changes. In the first case, there is only the PV system, the grid, and the load group. Comprehensive simulation results for this situation are given in Figs. 9.9–9.11 and Table 9.3.

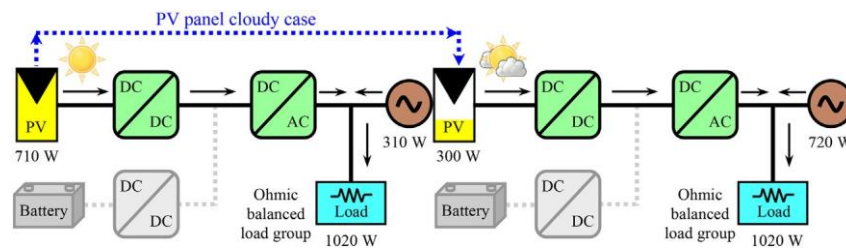


Fig. 9.8. Solar system (not include battery) and balanced load status.

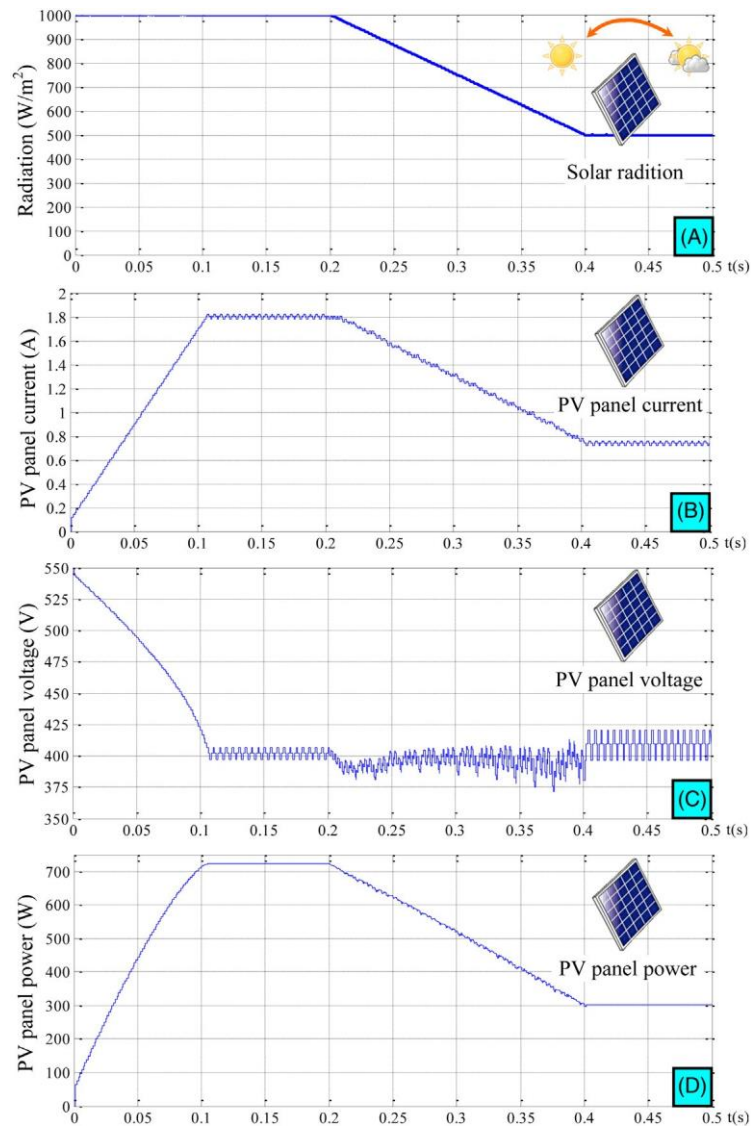


Fig. 9.9. The graphs of change.(A) Solar radiation, (B) PV panel current, (C) PV panel voltage, (D) PV panel power

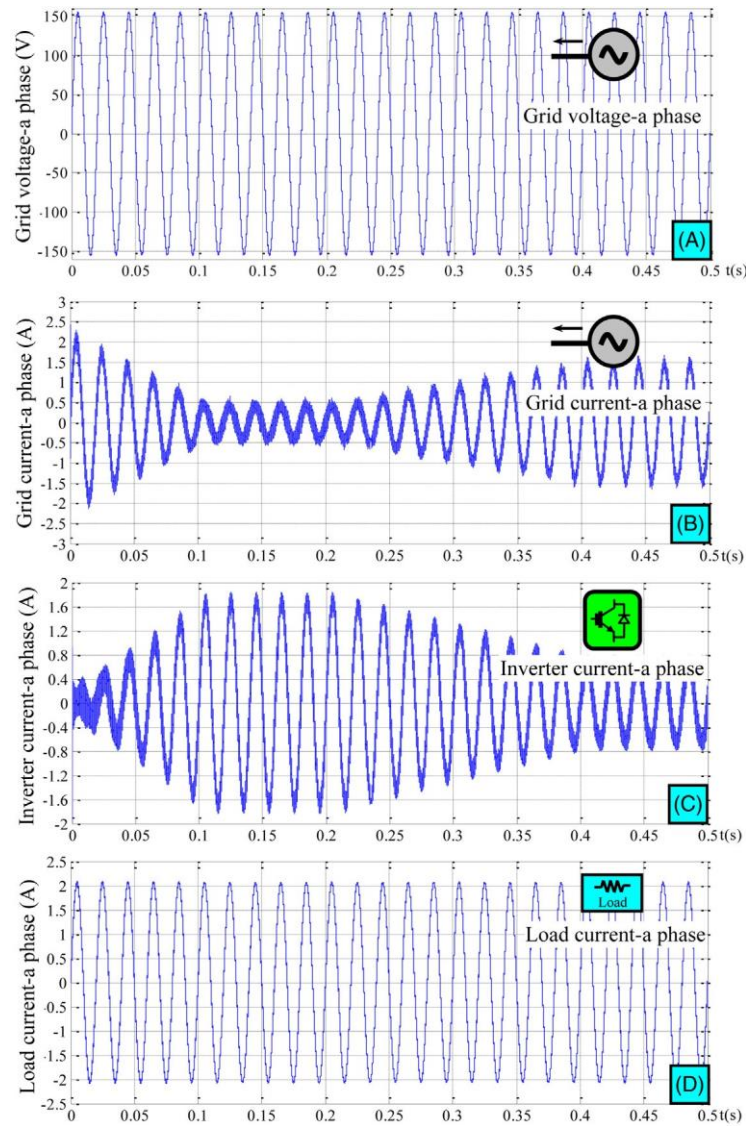


Fig. 9.10. The graphs of a-phase change.(A) Grid voltage, (B) grid current, (C) inverter current, (D) load current.

Since the neutral load current is zero in a balanced load status, the grid and inverter neutral current is also zero. The neutral current generated when there is an unbalanced load status is provided by the inverter depending on the PV panel power. A neutral current close to zero passes through the grid.

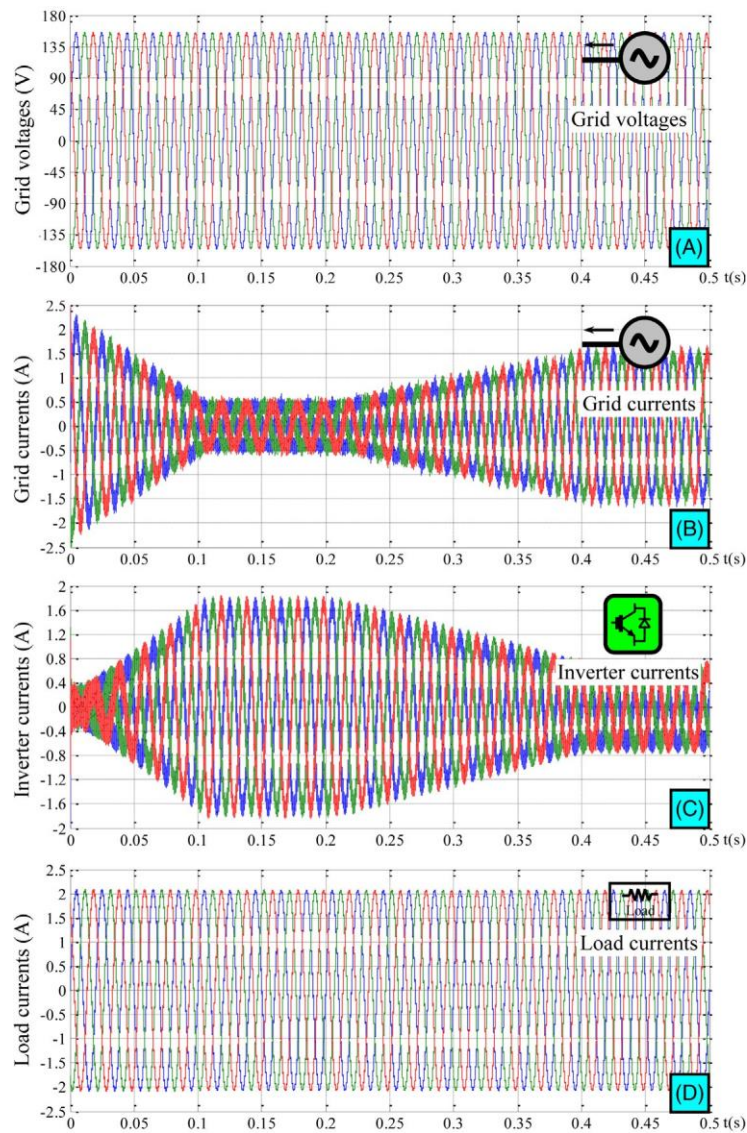


Fig. 9.11. The graphs of three-phase change.(A) Grid voltages, (B) grid currents,(C) inverter currents, (D) load currents.

In this case the solar radiation value is simulated according to its characteristic, which includes a variable weather. As soon as the system is first working, the MPPT algorithm finds the maximum power point in a short time in 0.1 second. This time is the time until the PV panel current starts from zero at first, until the current value at the maximum power point reaches the curve on the graph.

PV array and perturb & observe control algorithm

This period varies depending on the radiation value entered. When the balanced ohmic load ($75\ \Omega$, three-phase) is connected to the system, the load continuously draws a total of 1.46 A. Due to the radiation change, the inverter transfers current to the grid for 1.18 A for 0.1 second. Inverter provides some of the total current that the load must draw. The remaining current is drawn from the 0.28 A grid and the PV system's contribution to the grid is shown.

If the unbalanced ohmic load (A, B phase $75\ \Omega$, C phase $90\ \Omega$) is connected to the system, the load in C phase is 1.22 A. Loads in A and C phase draw a current of 1.46 A. Since the PV panel is operated under the same radiation conditions, it transfers the same current value to the grid for A, B phases. C phase varies depending on the load. For 0.1 second the inverter transfers 1.18 A current to the grid. The current value of 1.22 A of the load in C phase is drawn from the grid as 0.14 A. 1.18 A of the loads that draw a total of 1.46 A in A, and B phase is drawn from the inverter and 0.28 A from the grid. These values are given in detail in Table 9.3. Depending on the unbalanced load, the inverter is transferring different currents to the grid, and when the load is unbalanced, the unbalance is met by the inverter depending on the PV panel power. Since the neutral current is zero in the balanced load case, the inverter and the grid neutral current are also zero. In the case of unbalanced load, the difference current in the neutral line is provided by the inverter. Grid neutral current is close to zero. Inverter phase currents are given in detail in Figs. 9.12 and 9.13. The solar system supports single and unbalanced loads thanks to its three-phase four-arm inverter structure. An unbalanced load is connected to the system under the first solar radiation conditions. In the load group, there is an ohmic load of 280 W in A phase and 380 W in B and C phases. Thanks to the inverter structure, balanced load is demanded from the grid continuously.

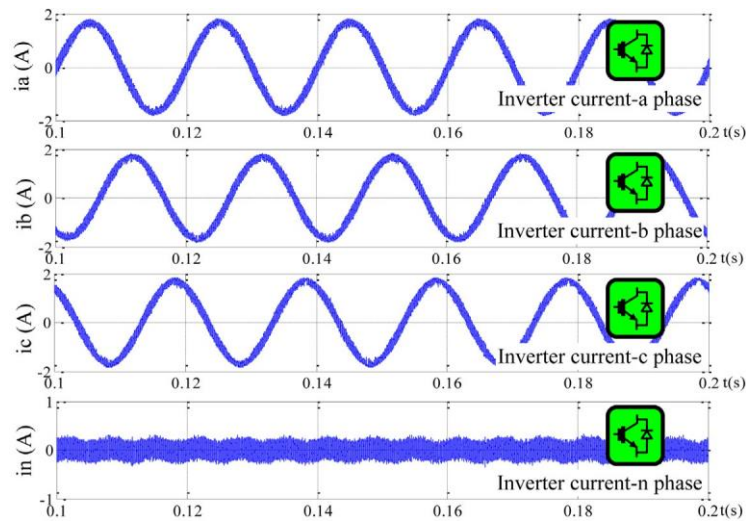


Fig. 9.12. Currents of inverter A phase, B phase, C phase, and neutral.

Table 9.3

Summary of the measured values in the PV solar system.

Parameters		0.1second			0.2 second			0.3 second			0.4 second			0.5 second		
Radiation(W/m ²)		1000			1000			752.5			500			500		
PV current (A)		1.69			1.80			1.31			0.74			0.74		
PV voltage (V)		420.3			402			400.3			409.7			409.7		
PV power (W)		714.5			723.6			528.3			303.2			303.2		
Balance d load (rms)	Grid current (A)	0.28			0.18			0.53			0.91			0.91		
	Inverter current (A)	1.18			1.28			0.93			0.55			0.55		
	Load current (A)	1.46			1.46			1.46			1.46			1.46		
Unbalan ced load (rms)	Phases	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
	Grid current (A)	0.28	0.14	0.118	0.07	0.53	0.43	0.91	0.79	0.91	0.79	0.91	0.79	0.91	0.79	0.79
	Inverter current (A)	1.18	1.08	1.28	1.15	0.93	0.79	0.55	0.43	0.55	0.43	0.55	0.43	0.55	0.43	0.43
	Load current (A)	1.46	1.22	1.46	1.22	1.46	1.46	1.46	1.46	1.46	1.22	1.46	1.22	1.46	1.46	1.22

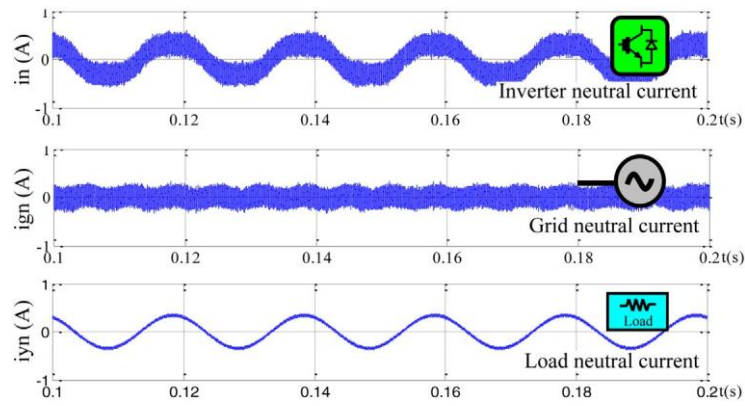


Fig. 9.13. Currents of inverter, grid, and load neutral.

The unbalance in the load group is met with the inverter. Solar system (not including battery) and unbalanced load status power flow is given in Fig. 9.14. First, the PV panel produces 710 W. The load group demands an unbalanced load of 960 W in total. In this case, there is only 250 W power flow from the grid to the load group. When it is cloudy, the PV panel generates 300 W. The difference power requested by the load is 660 W provided from the grid. Although PV panels have produced low power, the unbalance load demand is provided by the inverter thanks to its inverter structure. The graphs of three-phase change under unbalanced load, grid currents, inverter currents, and load currents, respectively, are given in detail in Fig. 9.15.

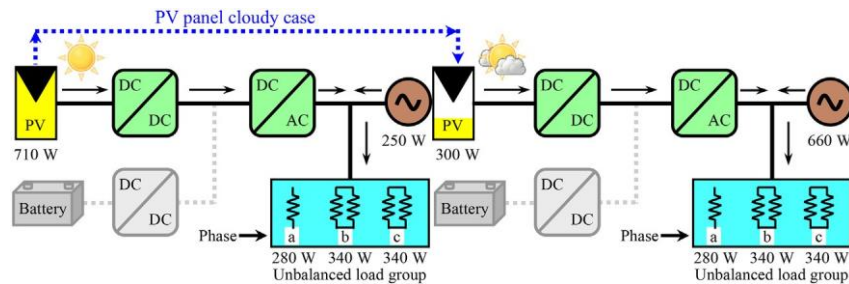


Fig. 9.14. Solar system (not including battery) and unbalanced load status.

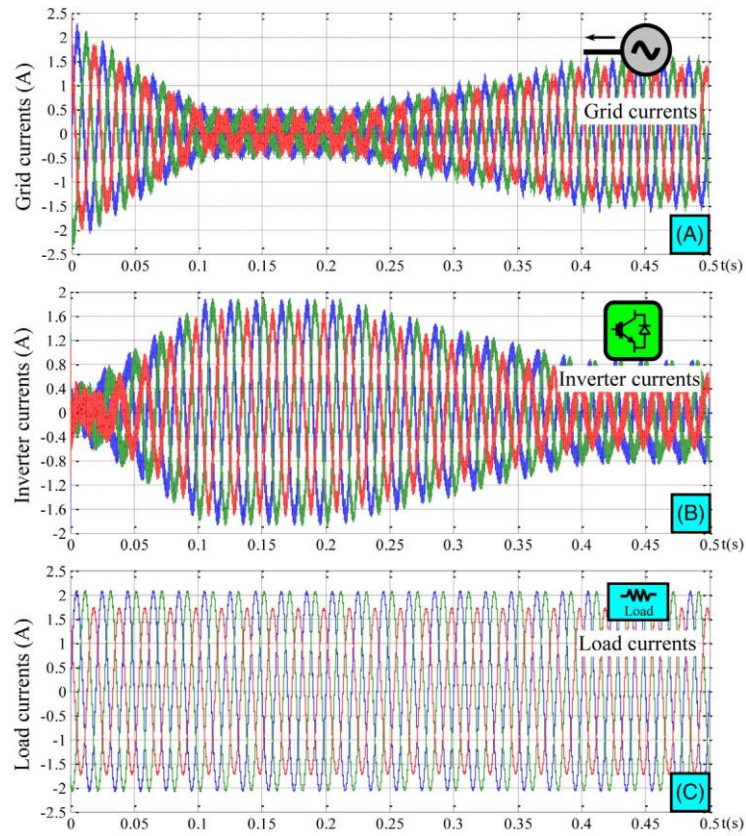


Fig. 9.15. The graphs of three-phase change under unbalanced load.(A) Grid currents, (B) inverter currents, (C) load currents.

The battery group was added to the solar system to which the PV panels are connected to the grid, and the results were examined. Lead–acid battery group with 48 V, 25 Ah, and 1200 Wh power capacity was added to the PV panels. Thus a solar hybrid structure containing an energy storage system was created. As in the previous tests, solar radiation changes are at the same value. In these test conditions the contribution of the battery group to the PV panels is clearly shown together with the graphic results. The power flow diagram of the solar hybrid system and the balanced load case containing the battery energy storage system is given in Fig. 9.17.

In this case, PV panel power generates power such as 710 W and then 300 W. The battery group is connected to the DC bus with a bidirectional DC/DC converter. DC bus voltage and battery group output voltage is 400 V. Thanks to the battery group, the voltage and the power fluctuations of the solar system in the DC bus are prevented. Depending on the power output of the PV panels, the battery group discharges at different current values for the continuous providing of the load. The battery group discharges with 0.9 A in the case of high solar radiation. Power demand of the load group is provided by solar hybrid system. In this case, there is no energy demand from the grid. When the solar radiation value changes, PV panels generate 300 W. Thanks to the solar

hybrid system structure, the discharge current of the battery group changes in real time and meets

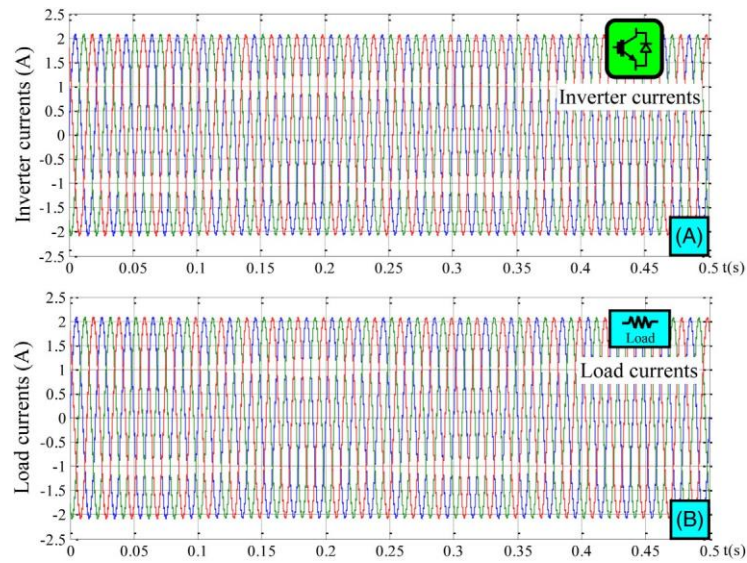


Fig. 9.16. The graphs of three-phase change.(A) Inverter currents, (B) load currents

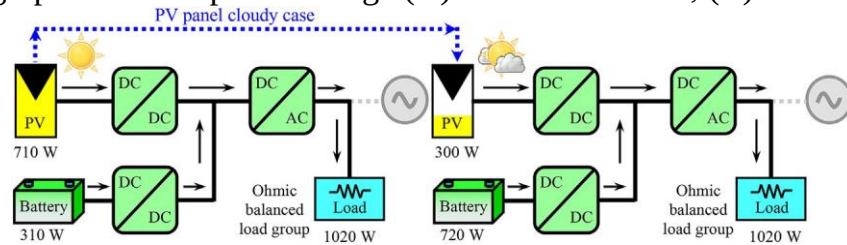


Fig. 9.17. Solar hybrid system (include battery) and balanced load status.

The load demand power with 1.8 A. The battery SOC is 77 % and the discharge decreases over time depending on the amount of current. Voltage, current, and SOC values of the battery group are given in Fig. 9.18, respectively. The inverter and the load of three-phase currents are given in Fig. 9.16. In this case, since there is no energy demand from the grid, the grid phase currents are 0. All power demanded by the load is provided by the PV panel and the battery group.

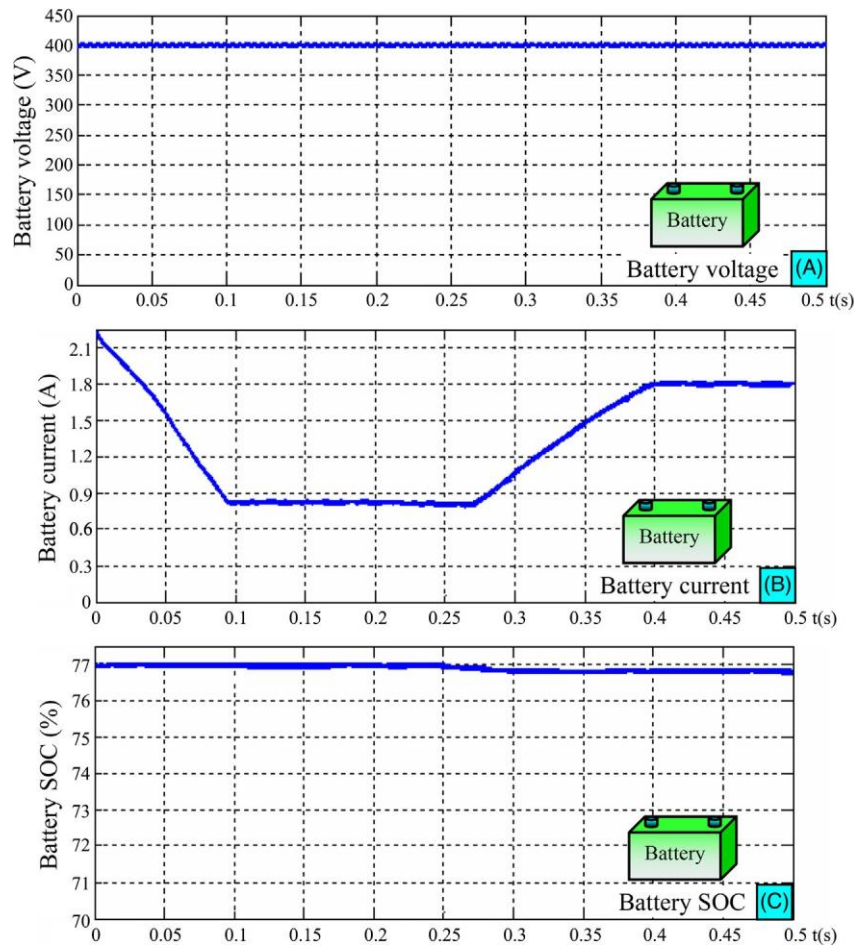


Fig. 9.18. The graphs of change.(A) Battery voltage, (B) battery current, (C) battery SOC.

One of the most important advantages of solar hybrid systems is a complementary factor for PV panels whose output characteristics change depending on the weather conditions. With the energy storage unit in the system the ripple effects are prevented in the DC bus. Thanks to the battery group, quality energy is provided and the continuity of energy is maintained. Solar hybrid systems occupy the grid as little as possible regarding energy use. In contrast, solar hybrid systems support the grid structure.

CONTROL QUESTIONS

1. What type of current do photovoltaic (PV) panels generate?
2. How many main application areas does solar photovoltaic panel technology have, and what are they?
3. What is the purpose of using solar hybrid system simulation?

4. Which method is used to continuously monitor the output power of a solar photovoltaic panel?
5. What do you understand by the term *perturbation*?
6. Why is the inverter current equal to zero under balanced load conditions?
7. Why is a constantly balanced load required from the power grid?
8. Why is grid synchronization important in grid-connected photovoltaic power systems?
9. What is the structure of a bidirectional DC/DC converter?
10. What is the block diagram structure of a solar photovoltaic panel?
11. What is the function of the battery bank?
12. Explain the difference between a battery model and a bidirectional DC/DC converter model.

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