

## Chapter 2

# Distributed Generation Plants

### 2.1 Combined Heat and Power Plants

Combined heat and power (CHP) or cogeneration systems are most promising as distributed energy resources (DERs) for microgrid (MG) applications. Their main advantage is energy-efficient power generation by judicious utilization of waste heat. Unlike fossil-fueled power plants, CHP systems capture and use the by-product heat locally for domestic and industrial/process heating purposes. Heat produced at moderate temperatures (100–180 °C) can also be used in absorption chillers for cooling. Simultaneous production of electricity, heat, and cooling is known as trigeneration or polygeneration.

#### 2.1.1 Introduction

By capturing excess heat, the CHP system allows better usage of energy than conventional generation, potentially reaching an efficiency of more than 80 compared with that of about 35 % for conventional power plants. It is most efficient when the heat is utilized locally. Overall efficiency is reduced if heat is to be transported over long distances using heavily insulated pipes, which are both expensive and inefficient. On the other hand, electricity can be transmitted over much longer distances for lesser energy loss. Thus, CHP plants can be located somewhat remotely from their electrical loads, but they must always be located close to the heat loads for better performance. CHP plants are commonly employed in district heating systems of big towns, hospitals, prisons, oil refineries, paper mills, and industrial plants with large heat loads.

Use of CHP plants has been found to lead to 35 % reduction in primary energy use compared to conventional power generation and heat-only boilers, 30 % reduction in emission with respect to coal-fired power plants and 10 % reduction in emission with respect to combined cycle gas turbine (CCGT) plants.

### ***2.1.2 Microcogeneration Systems***

Microcogeneration systems are usually installed in smaller premises like homes or small commercial buildings. They differ from larger CHP units not only in terms of their energy-producing capacities but also in matters of parameter-driven operation. Most large industrial CHP units generate electricity as the primary product with heat as secondary while micro-CHP systems generate heat as the primary commodity with electricity as a by-product. Thus, energy generation of micro-CHP systems is mainly dictated by the heat demand of the end users. Because of this operating model and the fluctuating electrical demand of the structures they operate in (like homes and small commercial buildings), micro-CHP systems often generate more electricity than is demanded.

Micro-CHP sets are basically microturbines coupled to single-shaft, high-speed (50,000–100,000 rpm) permanent magnet synchronous machines (SMs) with airfoil or magnetic bearings. They are provided with power electronic interfaces (PEIs) for connection to the electrical loads. They also have their own heat recovery systems for low and medium temperature heat extraction. Micro-CHP sets are reliable, robust, and cheap. They are available in the range of 10,100 kW capacity. The primary fuel is natural gas, propane, or liquid fuel, which permits clean combustion with low particulates. Biofuelled microturbines are also being considered as a possibility. During operation of a CHP set, the pressure of incoming air is raised after passing through the centrifugal compressor. Temperature of the compressed air is increased on passing through the heat exchanger. When the hot compressed air enters the combustion chamber, it is mixed with fuel and burnt. The high temperature combustion gases are expanded in the turbine to produce mechanical power, which in turn drives the permanent magnet SM to produce electrical power at high frequency. High-frequency output voltage is converted into DC using a rectifier and the DC voltage is reconverted into AC of 50/60 Hz of frequency as per necessity using an inverter interface.

By using micro-CHP plants, MGs can secure the following major advantages:

- Since transportation of electricity is far easier and more cost-effective than heat, it is much more suitable to place micro-CHP plants near heat loads than electrical loads. MG permits this energy optimal placement of CHP plants to achieve full utilization of heat. In case of necessity, fuel cells can also be used in the CHP plants for better utilization of the generated heat.
- The scale of heat generation for individual units is small. Therefore, micro-CHP plants have greater flexibility in matching several small heat loads. Technically, a MG can be designed with a judicious mix of waste and non-waste heat-producing generators so as to optimize the combined generation of heat and electricity. In spite of the above-mentioned flexibility, chances are still there of a mismatch in generating a proper mix of heat and electricity. Hence, attention must be paid to enhance this flexibility.

Micro-CHP systems are primarily based on the following technologies:

**Internal Combustion (IC) Engines**

**Stirling Engines**

**Microturbines**

**Fuel cells**

### ***2.1.3 Internal Combustion Engines***

In IC engines, fuel is burnt in air in a combustion chamber with or without oxidizers. Combustion creates high-temperature and high-pressure gases that are allowed to expand and act on movable bodies like pistons or rotors. IC engines are different from external combustion engines like steam engines and Stirling engines. The external combustion engines use the combustion process to heat a separate working fluid which then works by acting on the movable parts. IC engines include intermittent combustion engines (e.g., reciprocating engine, Wankel engine, and Bourkes engine) and the continuous combustion engines (e.g., Jet engines, rockets, and gas turbines (GTs)). The commonly used fuels are diesel, gasoline, and petroleum gas. Propane gas is also sometimes used as fuel. With some modifications to the fuel delivery components, most IC engines designed for gasoline can run on natural gas or liquefied petroleum gases. Liquid and gaseous biofuels, like ethanol and biodiesel, may also be used. Depending on the type of fuel, the IC engines are provided with spark ignition or compression ignition systems in their cylinders to initiate the fuel combustion process.

### ***2.1.4 Stirling Engines***

A stirling engine is a closed-cycle piston heat engine where the working gas is permanently contained within the cylinder. It is traditionally classified as an external combustion engine, though heat can also be supplied by noncombustible sources like solar, geothermal, chemical, and nuclear energy. Stirling engines use an external heat source and an external heat sink. Each is maintained within a limited temperature range and has sufficiently large temperature difference between them.

Stirling engines contain a fixed quantity of air, hydrogen, or helium gas as working fluid. Under normal operation, the engine is completely sealed and no gas can enter or leave the engine. Thus, no valves are required to control the intake and exhaust of gases unlike other piston engines. A Stirling engine cycles through four main processes, viz.

- (i) cooling,
- (ii) compression,
- (iii) heating and
- (iv) expansion,

accomplished by the movement of the working gas back and forth between hot and cold heat exchangers. The hot heat exchanger is kept in thermal contact with an external (primary) heat source like a fuel burner, while the cold heat exchanger is kept in thermal contact with an external heat sink like radiators. A change in gas temperature causes a corresponding change in its pressure, and the motion of the piston causes the gas to be alternately expanded and compressed. When the gas is heated, it expands in the sealed chamber and acts on the power piston to produce a power stroke. When the gas is cooled its pressure drops and then less work has to be done by the piston to compress the gas on the return stroke. This work difference yields the net power output.

Stirling engines are basically of three categories:

- (i) Alpha Stirling,
- (ii) Beta Stirling, and
- (iii) Gamma Stirling.

Stirling engines can be economically used as energy producers for CHP applications that utilize a heat source in conjunction with a secondary heating application, such as an industrial process. For such operations, the Stirling engines take the advantage of the temperature differential between the primary heat source and the heating application. The primary heat source enters the Stirling engine heater and produces mechanical power, and the waste heat from the engines heater is used to supply the secondary heating applications. The mechanical power produced by the engine is used to generate electricity as a secondary product. The overall process is very efficient and cost effective.

Stirling engines have several advantages over reciprocating engines. They can achieve high energy conversion efficiency of 80 %, though this is limited by non-ideal properties of the working gas and engine materials (such as friction, thermal conductivity, tensile strength, creep, and melting point). In contrast to IC engines, they are usually more energy efficient, quieter, and more reliable with lower maintenance requirements. But for the same power rating, a Stirling engine has larger size and higher capital cost than an IC engine. Hence, Stirling engines are being used only for those applications where the primary objective is to minimize the capital cost per kilowatt hour but not per kilowatt. The wider application of Stirling engine entirely depends on appropriate cost-benefit analysis. However, with growing concerns of rising energy costs, energy shortages, and environmental pollution caused by combustible fuels, the advantages of Stirling engines have become increasingly significant. They are being employed in various applications like water pumping and electrical generation from plentiful energy sources that are incompatible with the IC engine, such as solar energy, agricultural waste, and domestic refuse, as well as in CHP systems.

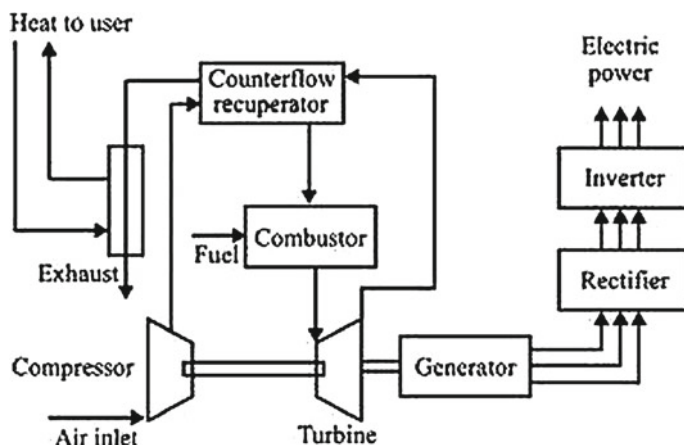


Fig. 2.1 Single-shaft microturbine

### 2.1.5 Microturbines

Microturbines are widely popular as generating units in distributed generation DG systems and as energy producers in CHP systems. At present they hold the maximum prospect to be used as microsources for MGs. Microturbines are small and simple-cycle GTs. The outputs of the microturbines range typically from around 25 to 300 kW. Performance improvement techniques used in microturbines include recuperation, low  $\text{NO}_x$  emission technologies, and the use of advanced materials such as ceramic for the hot section parts. Microturbines are available as single-shaft or split-shaft units. Single-shaft unit is a high-speed SM with the compressor and turbine mounted on the same shaft. For these machines, the turbine speed ranges from 50,000 to 120,000 rpm. By contrast, the split-shaft design uses a power turbine rotating at 3,000 rpm and a conventional generator connected via a gearbox for speed multiplication. Figure 2.1 shows a single-shaft microturbine system, while Fig. 2.2 shows a split-shaft one. Unlike traditional backup generators, microturbines are designed to operate for extended periods of time and require little maintenance. They can supply customers' base load requirements or can be used for standby, peak shaving, and cogeneration applications. They can run on most commercially available fuels, such as natural gas, propane, diesel, and kerosene, as well as on biofuels.

Microturbines have the following features:

1. Size. They are relatively smaller in size compared to other DERs.
2. Fuel-to-electricity conversion. They can reach the range of 2530 if the waste heat recovery is used for CHP applications, energy efficiency levels are greater than 80 %.
3.  $\text{NO}_x$  emissions. These are lower than 7 ppm for natural gas machines.

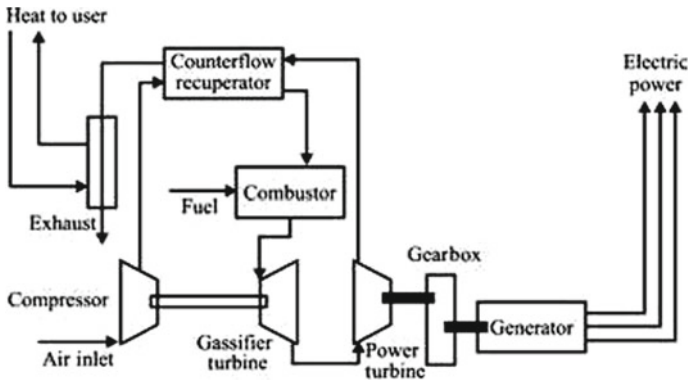


Fig. 2.2 Single-shaft microturbine

4. Operational life. They are designed for 11,000 h of operation between major overhauls with a service life of at least 45,000 h.
5. Economy of operation system costs are lower than 500 per kW. Cost of electricity is competitive with alternatives including grid power for market applications.
6. Fuel flexibility. It is capable of using alternative fuels, like natural gas, diesel, ethanol and landfill gas, and other biomass-derived liquids and gases.
7. Noise level. It has reduced level of noise and vibrations.
8. Installation. It has simpler installation procedure.

The research literature shows that there is an extensive thrust on the application of microturbine as DG systems. Research areas include simulation, offline/real-time studies and development of inverter interfaces for microturbine applications. Several research papers are available on the development of a single-stage axial flow microturbine for power generation, on the study of the facilities of the technology through relevant test results, on the development of active filters and adaptive control mechanisms for microturbines in hybrid power systems, etc. Studies also include development of dynamic models for microturbines to analyze their performance in islanded and grid-connected modes of operation and for cogeneration applications.

Most microturbines use permanent magnet synchronous generator (PMSG) or asynchronous generator for power generation. Ample research has been conducted on PMSG-coupled microturbines. However, very little has been reported on development and load-following performance analysis of microturbine models with synchronous generator (SYGN) in islanded and grid-connected modes. This area needs to be extensively investigated to resolve the technical issues for integrated operation of a microturbine with the main utility grid.

The main advantage of coupling an SG with a split-shaft microturbine is that it eliminates the use of the power converter. In this case, the generator is connected to the turbine via a gearbox to generate conventional 50/60 Hz power. Thus, the need for rectifiers and power converter units is completely eliminated. Moreover, the use of high-speed PMSG has disadvantages such as thermal stress, demagnetization

phenomena, centrifugal forces, rotor losses because of fringing effects, and high cost. The disadvantage of coupling induction (asynchronous) generators is that though they are cheaper and robust, their speed is load dependent and they cannot be connected to the grid without the use of expensive power converter systems. The use of PEIs for power conversion introduces harmonics in the system to reduce the output power quality (PQ). These harmonics are eliminated if an SG is used with a gearbox. Also, there are less chances of failure as the gearbox is a much simpler mechanical equipment as compared to complex power electronic devices. However, the main drawback of using a gearbox is that it consumes a fraction of generated power, thus reducing the efficiency of the system. Some manufacturing companies like Ingersoll-Rand Energy Systems, Ballard, Bowman, and Elliott use synchronous machines with their microturbines for both stand-alone and grid-connected operations.

### 2.1.6 Fuel Cells

A fuel cell converts chemical energy of a fuel directly into electrical energy. It consists of two electrodes (an anode and a cathode) and an electrolyte, retained in a matrix. The operation is similar to that of a storage battery except that the reactants and products are not stored, but are continuously fed to the cell. During operation, the hydrogen-rich fuel and oxidant (usually air) are separately supplied to the electrodes. Fuel is fed to the anode and oxidant to the cathode, and the two streams are separated by an electrode electrolyte system. Electrochemical oxidation and reduction take place at the electrodes to produce electricity. Heat and water are produced as by-products. Figure 2.3 shows the basic construction of a proton exchange membrane fuel cell.

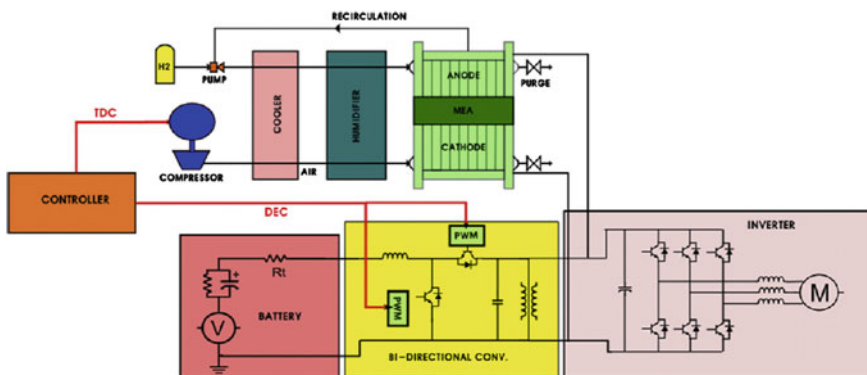


Fig. 2.3 Configuration of fuel cell system

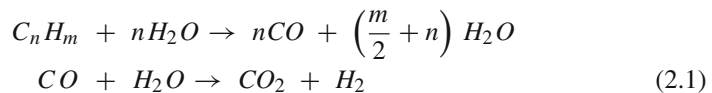
Three major subsystems exist in a typical pure hydrogen fuel cell system:

- Air supply with thermal management in which a reasonable flow rate and pressure are regulated to avoid oxygen starvation, water flooding of the membrane, and excessive auxiliary power consumption.
- Fuel supply, and
- Anode recirculation which is used to reduce hydrogen waste, maintain the pressure difference between anode and cathode to a minimum, and run the fuel in the anode in order to obtain better water management.

A fuel cell system with dynamic response is important for vehicular applications because fluctuations in power demand. A fuel cell and its subsystems usually do not operate at the optimal steady states designed by the manufacturer. Therefore, it is important to construct a precise PEM fuel cell dynamic model and adopt a robust control technique to satisfy the aforementioned power fluctuation requirements.

Fuel cells have several advantages over conventional generators. Due to higher efficiency and lower fuel oxidation temperature, fuel cells emit less  $\text{CO}_2$  and  $\text{NO}_x$  per kilowatt of power generated. Thus, they provide an eco-friendly energy source. As there are no moving parts, they are almost free from noise and vibration, robust and low maintenance. This makes them suitable for urban or suburban locations. Unlike gas and steam turbines, fuel cell efficiency increases at part-load conditions. Moreover, they can use a variety of fuels like natural gas, propane, landfill gas, anaerobic digester gas, diesel, naphtha, methanol, and hydrogen. This versatility ensures that this technology will not become obsolete due to the unavailability of fuels.

A single fuel cell produces output voltage less than 1 V. Therefore, to produce higher voltages, fuel cells are stacked on top of each other and are series connected forming a fuel cell system. Electrical efficiencies of fuel cells lie between 36 % and 60 %, depending on the type and system configuration. By using conventional heat recovery equipment, overall efficiency can be enhanced to about 85 %. Steam reforming of liquid hydrocarbons ( $C_n H_m$ ) is a potential way of providing hydrogen-rich fuel for fuel cells. This is preferred because storage of hydrogen is quite hazardous and expensive. Reformers provide a running stream of hydrogen without having to use bulky pressurized hydrogen tanks or hydrogen vehicles for distribution. The endothermic reaction that occurs in the reforming process in the presence of a catalyst is



Carbon monoxide (CO) combines with steam to produce more hydrogen through the water gas shift reaction. Extensive research is going on to design reformer fuel cell system in spite of the following challenges:



- Steam reforming can utilize liquid hydrocarbon fuels like ethanol and biodiesel, but these fuels may not be available in sufficiently large quantities to provide a continuous stream of hydrogen.
- As the reforming reaction takes place at high temperatures, fuel cells have high start-up time and require costly temperature-resistant materials.
- The catalyst is very expensive and the sulfur compounds present in the fuel may poison certain catalysts, making it difficult to run this type of system on ordinary gasoline.
- CO produced in the reaction may poison the fuel cell membrane and may degrade its performance. In that case, complicated CO removal systems must be incorporated into the system.
- Thermodynamic efficiency of the process depends on the purity of the hydrogen product. Normally, thermodynamic efficiency lies between 70 and 85 %.

## 2.2 Renewable Energy Generation

Renewable power generation can help countries meet their sustainable development goals through provision of access to clean, secure, reliable, and affordable energy. Renewable energy has gone mainstream, accounting for the majority of capacity additions in power generation today [4, 29, 31]. Tens of gigawatts of wind, hydropower, and solar photovoltaic (PV) capacity are installed worldwide every year in a renewable energy market that is worth more than a hundred billion USD annually. Other renewable power technology markets are also emerging. Recent years have seen dramatic reductions in renewable energy technologies costs as a result of R&D and accelerated deployment. Yet policy-makers are often not aware of the latest cost data.

### 2.2.1 *Wind Power Plants*

Wind turbines (WTs) operate on a simple principle. The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins a generator to create electricity. WTs are mounted on a tower to capture the most energy. At 100 feet (30m) or more above ground, they can take advantage of faster and less turbulent wind. WTs can be used to produce electricity for a single home or building, or they can be connected to an electricity grid (shown here) for more widespread electricity distribution.

We have been harnessing the wind's energy for hundreds of years. From old Holland to farms in the United States, windmills have been used for pumping water or grinding grain. Today, the windmill's modern equivalent WT can use the wind's energy to generate electricity.

WTs, like windmills, are mounted on a tower to capture the most energy. At 100 feet (30m) or more aboveground, they can take advantage of the faster and less

turbulent wind. Turbines catch the wind's energy with their propeller-like blades. Usually, two or three blades are mounted on a shaft to form a rotor.

A blade acts much like an airplane wing. When the wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft spins a generator to make electricity.

WTs can be used as stand-alone applications, or they can be connected to a utility power grid or even combined with a PV (solar cell) system. For utility-scale (megawatt-sized) sources of wind energy, a large number of WTs are usually built close together to form a wind plant, also referred to as a wind farm. Several electricity providers today use wind plants to supply power to their customers.

Stand-alone WTs are typically used for water pumping or communications. However, homeowners, farmers, and ranchers in windy areas can also use WTs as a way to cut their electric bills.

Small wind systems also have potential as DERs. DERs refer to a variety of small, modular power-generating technologies that can be combined to improve the operation of the electricity delivery system.

Although all WTs operate on similar principles, several varieties are in use today. These include horizontal axis turbines and vertical axis turbines.

### **Horizontal Axis Turbines**

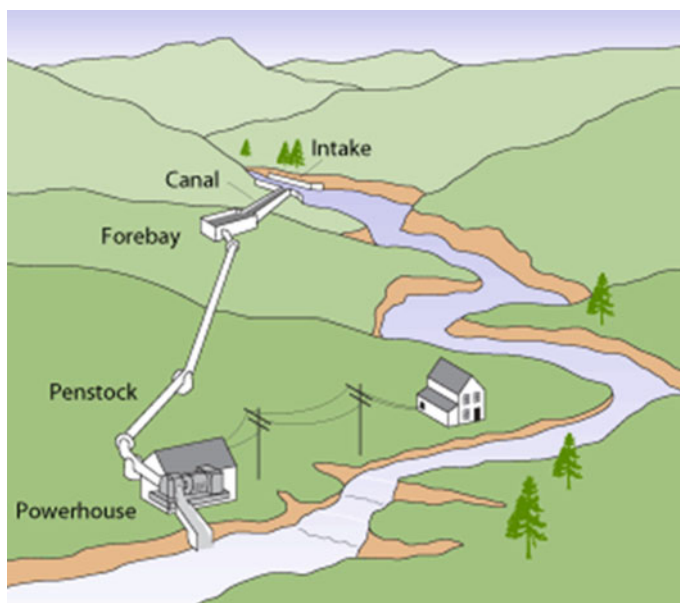
Horizontal axis turbines are the most common turbine configuration used today. They consist of a tall tower, atop which sits a fan-like rotor that faces into or away from the wind, a generator, a controller, and other components. Most horizontal axis turbines built today are two- or three-bladed.

Horizontal axis turbines sit high atop towers to take advantage of the stronger and less turbulent wind at 100 feet (30m) or more above ground. Each blade acts like an airplane wing, so when wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, which causes the rotor to turn. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft spins a generator to make electricity.

### **Vertical Axis Turbines**

Vertical axis turbines are of two types: *Savonius* and *Darrieus*. Neither type is in wide use.

The *Darrieus* turbine was invented in France in the 1920s. Often described as looking like an eggbeater, it has vertical blades that rotate into and out of the wind.



**Fig. 2.4** Schematic of run-of-the-river microhydropower systems

Using aerodynamic lift, it can capture more energy than drag devices. The Giromill and cycloturbine are variants on the Darrieus turbine.

The *Savonius* turbine is S-shaped if viewed from above. This drag-type turbine turns relatively slowly but yields a high torque. It is useful for grinding grain, pumping water, and many other tasks, but its slow rotational speeds are not good for generating electricity.

In addition, windmills are still used for a variety of purposes. Windmills have been used by humans since at least 200 B.C. for grinding grain and pumping water. By the 1900s, windmills were used on farms and ranches in the United States to pump water and, later, to produce electricity. Windmills have more blades than modern WTs, and they rely on drag to rotate the blades.

### ***2.2.2 Small-Scale Hydrogeneration***

All hydropower systems use the energy of flowing water to produce electricity or mechanical energy. Although there are, several ways to harness moving water to produce energy, “run-of-the-river systems,” which do not require large storage reservoirs, are most often used for microhydropower systems (Fig. 2.4).

For run-of-the-river microhydropower systems, a portion of a river’s water is diverted to a water conveyance channel, pipeline, or pressurized pipeline (called a penstock) that delivers it to a turbine or waterwheel. The moving water rotates the wheel or turbine, which spins a shaft. The motion of the shaft can be used for

mechanical processes, such as pumping water, or it can be used to power an alternator or generator to generate electricity.

Run-of-the-river microhydropower systems consist of:

- A water conveyance, which is a channel, pipeline, or pressurized pipeline (penstock) that delivers the water
- A turbine, pump, or waterwheel, which transforms the energy of flowing water into rotational energy
- An alternator or generator, which transforms the rotational energy into electricity
- A regulator, which controls the generator
- Wiring, which delivers the electricity.

Many systems also use an inverter to convert the low-voltage direct current (LVDC) electricity produced by the system into 120 or 240 V of AC electricity.

Commercially available turbines and generators are usually sold as a package. Do-it-yourself systems require careful matching of a generator with the turbine horsepower and speed.

Whether a microhydropower system will be grid-connected or stand-alone will determine its final balance of system components. For example, some stand-alone systems use batteries to store the electricity generated by the system. However, because hydropower resources tend to be more seasonal in nature than wind or solar resources, batteries may not always be practical. If batteries are used, they should be located as close to the turbine as possible because it is difficult to transmit low-voltage (LV) power over long distances. Dams or diversion structures are rarely used in microhydropower projects. They are an added expense and require professional assistance from a civil engineer. In addition, dams increase the potential for environmental and maintenance problems.

## 2.3 Solar Photovoltaic Generation

The modern form of the PV, also called solar cells, was invented in 1954 at Bell Telephone Laboratories. Today, PV is one of the fastest growing renewable energy technologies and it is expected that it will play a major role in the future global electricity generation mix [16].

PV technology offers a number of significant benefits, including:

- Solar power is a renewable resource that is available everywhere in the world.
- Solar PV technologies are small and highly modular and can be used virtually anywhere, unlike many other electricity generation technologies.
- Unlike conventional power plants using coal, nuclear, oil and gas; solar PV has no fuel costs and relatively low operation and maintenance (O&M) costs. PV can therefore offer a price hedge against volatile fossil fuel prices.
- PV, although variable, has a high coincidence with peak electricity demand driven by cooling in summer and year round in hot countries.

### 2.3.1 Technology Basics

Photo of a large silicon solar array on a roof with a blue sky and trees in background. A large silicon solar array installed on the roof of a commercial building. Photo of a traditional-looking home with blue solar tiles integrated into the brown roof. Thin-film solar tiles installed on the roof of a home in Ohio. Photo of a long, blue solar array in a field of grass. A large solar array in Germany.

Solar cells, also called PV cells by scientists, convert sunlight directly into electricity. PV gets its name from the process of converting light (photons) to electricity (voltage), which is called the PV effect. The PV effect was discovered in 1954, when scientists at Bell Telephone discovered that silicon (an element found in sand) created an electric charge when exposed to sunlight. Soon solar cells were being used to power space satellites and smaller items like calculators and watches. Today, thousands of people power their homes and businesses with individual solar PV systems. Utility companies are also using PV technology for large power stations. Solar panels used to power homes and businesses are typically made from solar cells combined into modules that hold about 40 cells. A typical home will use about 10 to 20 solar panels to power the home. The panels are mounted at a fixed angle facing south, or they can be mounted on a tracking device that follows the sun, allowing them to capture the most sunlight. Many solar panels combined together to create one system is called a solar array. For large electric utility or industrial applications, hundreds of solar arrays are interconnected to form a large utility-scale PV system.

Traditional solar cells are made from silicon, are usually flat plate, and generally are the most efficient. Second-generation solar cells are called thin-film solar cells because they are made from amorphous silicon or non-silicon materials such as cadmium telluride. Thin-film solar cells use layers of semiconductor materials only a few micrometers thick. Because of their flexibility, thin-film solar cells can double as rooftop shingles and tiles, building facades, or the glazing for skylights.

Third-generation solar cells are being made from a variety of new materials besides silicon, including solar inks using conventional printing press technologies, solar dyes, and conductive plastics. Some new solar cells use plastic lenses or mirrors to concentrate sunlight onto a very small piece of high efficiency PV material. The PV material is more expensive, but because so little is needed, these systems are becoming cost effective for use by utilities and industry. However, because the lenses must be pointed at the sun, the use of concentrating collectors is limited to the sunniest parts of the country.

PV cell technologies are usually classified into three generations, depending on the basic material used and the level of commercial maturity:

- **First-generation PV systems** (fully commercial) use the wafer-based crystalline silicon (c-Si) technology, either single crystalline (sc-Si) or multicrystalline (mc-Si).
- **Second-generation PV systems** (early market deployment) are based on thin-film PV technologies and generally include three main families:



**Fig. 2.5** A large silicon solar array installed on the roof of a commercial building

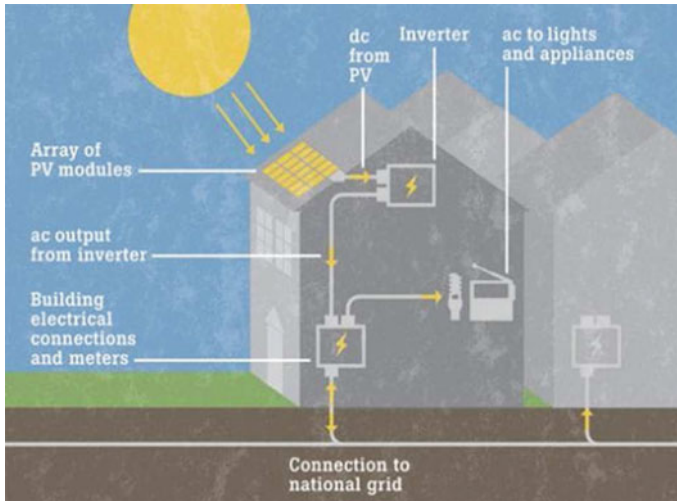
1. Amorphous (a-Si) and micromorph silicon (a- $S_i/c-S_i$ );
  2. Cadmium–Telluride ( $C_dT_e$ ); and
  3. Copper–Indium–Selenide (CIS) and Copper–Indium–Gallium–Diselenide (CIGS).
- **Third-generation PV systems** include technologies, such as concentrating PV (CPV) and organic PV cells that are still under demonstration or have not yet been widely commercialized, as well as novel concepts under development (Fig. 2.5).

### 2.3.2 Grid-Connected Solar Systems

Solar panels that harness the sun's power to generate electricity provide clean power for homes, communities and businesses, and help cut global carbon emissions.

Solar PV modules generate electricity from sunlight, which can be fed into the mains electricity supply of a building or sold to the public electricity grid. Reducing the need for fossil fuel generation, the growing grid-connected solar PV sector across the globe is helping create jobs, enabling families and businesses to save money, and cut greenhouse emissions.

PV modules use semiconductor materials to generate DC electricity from sunlight. A large area is needed to collect as much sunlight as possible, so the semiconductor is either made into thin, flat, crystalline cells, or deposited as a very thin continuous layer onto a support material. The cells are wired together and sealed into a weather-proof module, with electrical connectors added. Modern modules for grid connection



**Fig. 2.6** PV connection system

usually have between 48 and 72 cells and produce DC voltages of typically 25–40 volts, with a rated output (see box) of between 150 and 250 Wp.

In order to supply electricity into a mains electricity system, the DC output from the module must be converted to AC at the correct voltage and frequency. An electronic inverter is used to do this. Generally, a number of PV modules are connected in series to provide a higher DC voltage to the inverter input, and sometimes several of these series strings are connected in parallel, so that a single inverter can be used for 50 or more modules. Modern inverters are very efficient (typically 97%), and use electronic control systems to ensure that the PV array keeps working at its optimum voltage. They also incorporate safety systems as required in the country of use (Fig. 2.6).

PV modules are specified by their watt-peak (Wp) rating, which is the power generated at a solar radiation level of  $1000\text{ W/m}^2$ , equivalent to bright sun in the tropics. They still work fine with less solar radiation. The voltage produced by a PV module is largely determined by the semiconductor material and the number of cells, and varies only slightly with the amount of solar radiation. The electrical current and the power generated are proportional to the amount of solar radiation.

### **2.3.3 Future Trends**

Grid-connected systems do not usually include batteries for storage, because the mains grid can accept or provide power as needed. However, if rechargeable batteries are included, a grid-connected PV system can be used as a stand-alone AC supply



in the event of a power cut, to allow essential loads to keep working. Ashden winner Deng solar provided a 9.2 kWp grid backup system for the central courts in Accra, Ghana, which maintains lighting and thus enables court business to keep going during power cuts. The Aryavart Gramin Bank has provided PV grid backup systems for its rural branches, so that their IT systems and cash machines still work during power cuts and voltage fluctuations.

Looking ahead at the future, the price of PV modules is decreasing rapidly. For crystalline cells, new ways of processing silicon and increased volume manufacture are driving down prices. The market share of thin-film PV is growing rapidly as materials which have been proved in the laboratory go into volume production, and these promise even greater price reductions. However, there is less potential for price reduction in the balance of system, and these costs will soon dominate the overall system cost. Because of the decreasing prices, the rapid growth in the market for grid-connected PV is expected to continue even if government support is reduced. The market will really take off when electricity from PV becomes cheaper than other grid sources. When PV feeds directly into a building supply, this grid parity price is the consumer purchase price, currently 10–20 US cents per kWh. A recent roadmap by the International Energy Agency suggests that this point may be reached in sunny countries by 2020. For systems connecting directly to the national grid, the grid parity price is less than 5 US cents per kWh. The roadmap suggests that even this point could be reached by 2030, and that PV could then be supplying about 5 % of global electricity.

## 2.4 Small Wind Turbine Systems

In the past two decades, we have witnessed a dramatic increase in the penetration of the WT power generation worldwide. In turn, this growing trend has a major impact on stimulating the research in the power processing field aiming at optimizing the energy extraction from the wind and the energy injection into the grid [41]. Particular attention has been recently focused on DG through small WTs (power unit 200 kW) because of: lower impact on the landscape, lower noise level, grid codes, and national laws imposing simpler grid connection and higher feed-in tariffs and capability to work in island mode for isolated communities [34]. In general, it can be observed that the maximum WT size increases in the case of wind diesel system with battery, and the maximum WT size increases in case of grid connection. The field of small generation was dominated by the use of asynchronous generators directly connected to the grid/load and more recently by PMSG with a diode rectifier, boost converter and inverter [45]. The use of an high number of pole pairs allow the PMSG to operate at low speed without decreasing the efficiency, thus allowing to avoid the gearbox [24]. The use of a diode bridge reduces cost and control algorithm complexity [12].

Moreover, the well-known six-pulse DC voltage waveform allow to implement a simple estimator of the rotor speed. The generator low frequency harmonics (5th and 7th) can be reduced, thanks to the DC inductor that unfortunately has a



negative effect on the power factor. Moreover, the extracted power decreases as the wind speed increases due to the major effect of diode commutation and at low speed due to possible discontinuous operation of the DC/DC converter. Hence, for power levels in the order of tens of kW, these generators will use a back-to-back converter leading to a 5, 15 % more power. Besides the choice of the power converter configuration, the control issues in PMSG-based small WT systems are many [14, 21], as shown Fig. 2.8. Simultaneously, in the literature, a lot of attention is committed to DSP and FPGA control system implementation of generator and converters for WT applications [5, 20, 44].

On the generator side two main control issues are present:

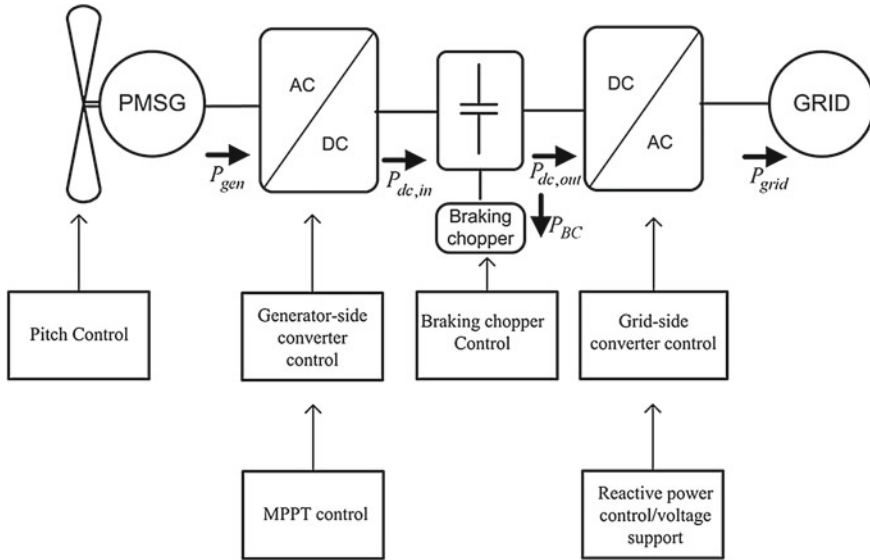
- the tracking of the maximum power without using an anemometer, and
- the estimation of the rotor position and speed since the use of a sensor is not always practical.

In case of variable wind conditions that are the most common at low altitude, control strategies involving maximum power point tracking (MPPT) algorithms based on an operational seeking algorithm or a wind speed estimator can be implemented [1, 13, 19, 24, 42, 46].

### 2.4.1 Types of Wind Turbine Systems

Several types of generators can be adopted in wind power turbines: DC and AC types, parallel and compound DC generators, permanent magnets or electrical field excited, asynchronous or synchronous generators. The right choice depends on the primary source, the type of load and the speed of the turbine. Besides, systems differ with respect to their applications, whether they are stand-alone or connected to the grid [33]. The most adopted WT generator for medium power systems is the doubly fed induction generator (DFIG) that could be used even in stand-alone operation [11, 17, 25]. However, typically, in small WTS for stand-alone applications, the choice is between variable-speed asynchronous and synchronous generators [40]. Variable-speed asynchronous generators can easily operate in parallel with large power systems, since the utility grid controls voltage and frequency, while static and reactive compensating capacitors can be used for correction of the power factor and harmonic reduction. Abrupt speed changes due to load or primary source changes are easily absorbed by the solid rotor of the asynchronous generator, and current surges can be effectively damped without demagnetization issues [39].

Over the last years, the most common solution for wind generator is based on permanent magnet SMs directly connected to the turbine [8, 23, 32, 43]. This solution is particularly favorable as it reduces the frequency and the costs of maintenance operations. In fact these generators are self-excited, allowing operation at high-power factor and high efficiency. Moreover, multipolar PMSG does not need the gearbox to adapt the rotor speed to the blade speed. This advantage becomes crucial for WT installation in harsh environment characterized by low temperature (Fig. 2.7).

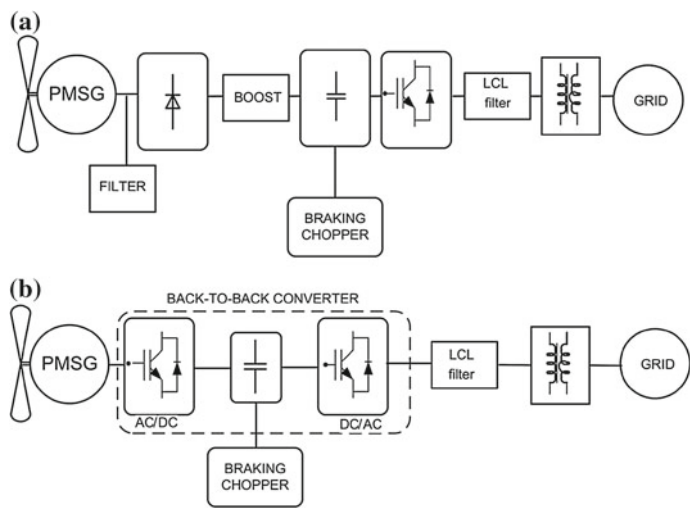


**Fig. 2.7** Control issues in PMSG-based small wind turbine systems

Figure 2.8a shows a PMSG connected to the grid through three converters: a diode bridge rectifier, a boost converter, and an inverter. The DC/DC boost converter is used to control the generator [3, 18].

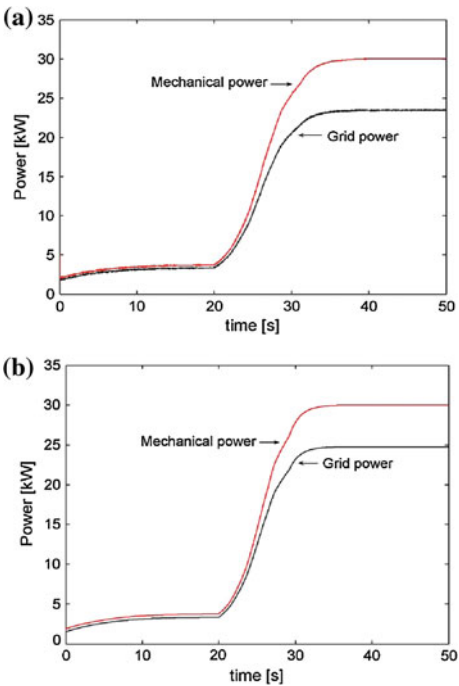
Figure 2.8b shows a PMSG connected to the grid through a bidirectional converter. It consists of two VSI-PWM converters connected by a storage capacitor: the converter connected to the generator is used as a rectifier, while the converter connected to the grid is used as an inverter. To achieve full control of the output, the DC-link voltage must be boosted to a level higher than the amplitude of the grid voltage. The power flow of the grid-side converter is controlled in order to keep the DC-link voltage constant, while the control of the generator side is set to suit the magnetization demand and the reference speed or torque. A technical advantage of this topology is the capacitor decoupling between the grid converter and the generator converter. Besides affording some protection, this decoupling offers separate control of the two converters, allowing compensation of asymmetry both on the generator side and on the grid side, independently.

The two above-mentioned topologies give rise to different efficiencies in the power processing, as shown by Fig. 2.9, where the mechanical power and the power injected into the grid are shown in case of a diode bridge rectifier plus boost converter (a) and back-to-back converter (b).



**Fig. 2.8** Wind turbine system. **a** Diode bridge rectifier and boost converter. **b** Back-to-back converter

**Fig. 2.9** Comparison between the mechanical power and the grid power. **a** Diode bridge rectifier. **b** Back-to-back converter

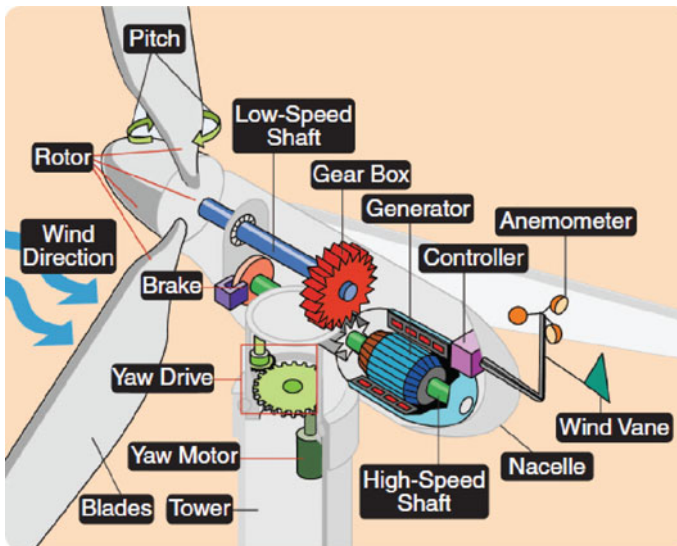


### 2.4.2 Wind Turbine Fundamentals

This section makes use of the tutorial paper [35]. Wind is recognized worldwide as a cost-effective, environmentally friendly solution to energy shortages. According to the World Wind Energy Association (WWEA), the global installed capacity of WTs grew at an average rate of 27 % per year over the years 2005–2009. Although a WT can be built in either a vertical axis or horizontal axis configuration, focus will be on horizontal axis wind turbines (HAWTs) because they dominate the utility-scale WT market. At the utility scale, HAWTs have aerodynamic and practical advantages [9, 22]. The generating capacity of commercially available HAWTs ranges from less than 1 kW to several megawatts.

The main components of a HAWT that are visible from the ground are the tower, nacelle, and rotor, as shown in Fig. 2.10. The airfoil-shaped blades capture the kinetic energy of the wind and transform it into the rotational kinetic energy of the WTs rotor. The rotor drives the low-speed shaft, which in turn drives the gearbox. The gearbox steps up the rotational speed and drives the generator by means of the high-speed shaft. The gearbox, high-speed shaft, and generator are housed in the nacelle, along with part of the low-speed shaft. Direct drive configurations without gearboxes are being developed to eliminate costly gearbox failures.

WTs may be variable or fixed speed. Variable-speed turbines tend to operate closer to their maximum aerodynamic efficiency for a higher fraction of the time but require electrical power processing so that the generated electricity can be fed into the electrical grid at the proper frequency. Variable-speed turbines are more



**Fig. 2.10** Comparison between the mechanical power and the grid power. **a** Diode bridge rectifier. **b** The main components of a HAWT

cost-effective and thus more popular than constant-speed turbines at the utility scale because of improvements in generator and power electronics technologies. Variable-speed operation can also reduce turbine loads, since sudden increases in wind energy due to gusts can be absorbed by an increase in rotor speed rather than by component bending.

The goals and strategies of WT control are affected by the turbine configuration. A HAWT can be upwind, with the rotor on the upwind side of the tower, or downwind, with the rotor on the downwind side of the tower. This choice affects the turbine dynamics and thus the structural design. A WT can also be variable pitch or fixed pitch, meaning that the blades may or may not be able to rotate about their longitudinal axes. Variable-pitch turbines might allow all or part of their blades to rotate along the pitch axis. Fixed pitch machines are less expensive to build, but the ability of variable-pitch turbines to mitigate loads and affect the aerodynamic torque has driven their dominance in modern utility-scale turbine markets.

### 2.4.3 Control Loops

The main loops of WT control systems are shown in Fig. 2.11. Since the wind speed varies across the rotor plane, wind speed point measurements convey only a small part of the information about the wind inflow. Rotor speed is the only measurement required for the baseline generator torque and blade pitch controllers.

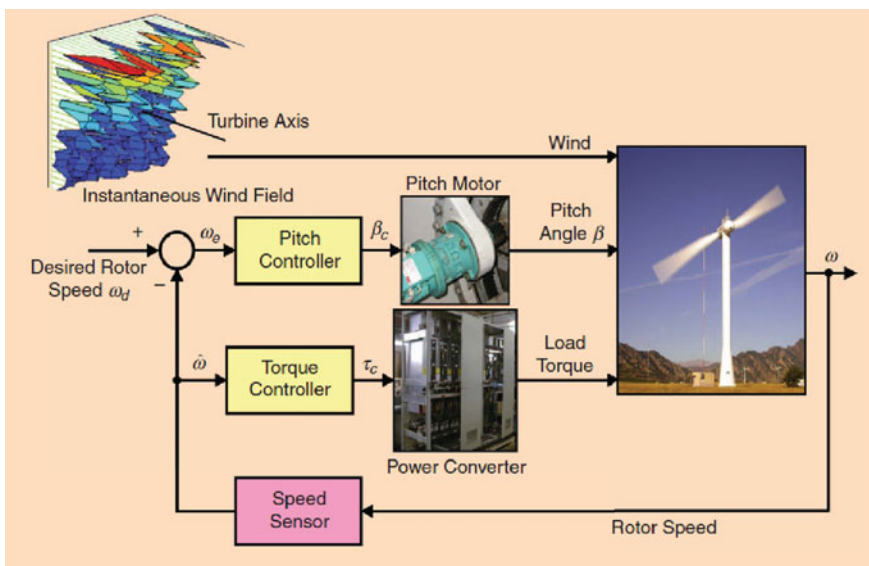


Fig. 2.11 Wind turbine control feedback loops

### 2.4.4 Generator Side Control

In this section, the generator model and its control is presented. The generator is modeled by the following voltage equations in the rotor reference frame (dq-axes) [7]:

$$\begin{aligned} v_{sd} &= -R_s i_{sd} - \frac{d\lambda_{sd}}{dt} + \omega_r \lambda_{sq} \\ v_{sq} &= -R_s i_{sq} - \frac{d\lambda_{sq}}{dt} + \omega_r \lambda_{sd} \end{aligned} \quad (2.2)$$

where  $\lambda_{sd}$  and  $\lambda_{sq}$  are d and q flux linkages

$$\lambda_{sd} = L_s i_{sd} + \psi_{PM}, \quad \lambda_{sq} = L_s i_{sq} \quad (2.3)$$

with  $\psi_{PM}$  is the flux of the permanent magnets. Let  $m_s$  be the number of phases and  $n_p$  be the pole pairs, then the electromagnetic torque is

$$T_e = \frac{m_s n_p}{2} (\lambda_{sq} i_{sd} - \lambda_{sd} i_{sq}) \quad (2.4)$$

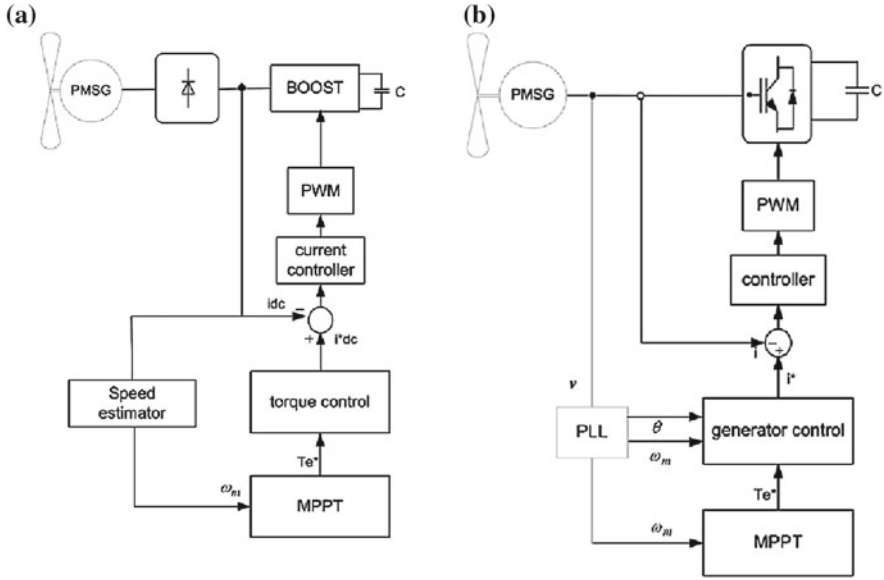
Using (2.3), we have

$$T_e = -\frac{m_s n_p}{2} \psi_{PM} i_{sq} = -K_c i_{sq} \quad (2.5)$$

where  $K_c$  is the torque constant representing the proportional coefficient between  $T_e$  and  $i_{sq}$ .

### 2.4.5 Boost Converter Control

The schemes of the generator side control in case a diode bridge plus boost converter is used or a pulse-width modulation (PWM) rectifier is used are shown in Fig. 2.12. In the first case, the speed is estimated considering the six pulse fluctuation in the DC current and the torque is controlled controlling this current as it will be shown in the following. In the second case, a vector control is adopted hence the knowledge of the position of the electromagnetic force is needed, and a phase-locked loop (PLL) is used to estimate it as it will be discussed in the following section. In Fig. 2.12a, the controller for the first topology is shown. The rotor speed determines the torque reference, which is used to calculate the DC current reference value. The diode bridge rectifier can be modeled by the following equations:



**Fig. 2.12** Generator side converter control. **a** Diode bridge rectifier and boost converter. **b** Back-to-back converter

$$v_{dc} = v_a S_a + v_b S_b + v_c S_c \quad (2.6)$$

$$i_a = S_a i_{dc},$$

$$i_b = S_b i_{dc},$$

$$i_c = S_c i_{dc}, \quad (2.7)$$

In effect, (2.6) and (2.7) represent the rectifier **DC** voltage and the rectifier **AC** currents based on the switching functions

$$\begin{aligned} S_a &= \sum_{k=1}^{\infty} \hat{S}_{ak} \sin(k\omega t), \\ S_b &= \sum_{k=1}^{\infty} \hat{S}_{bk} \sin\left(k\left(\omega t - \frac{2\pi}{3}\right)\right), \\ S_c &= \sum_{k=1}^{\infty} \hat{S}_{ck} \sin\left(k\left(\omega t - \frac{4\pi}{3}\right)\right), \end{aligned} \quad (2.8)$$

For  $k = 1$ , it yields

$$S_{a1} = \frac{2\sqrt{3}}{\pi} \sin(\omega t), \quad (2.9)$$

It is easy to show that the relation existing between  $I_1$ , the fundamental component of the AC current and  $I_{ds}$ , the DC current is

$$I_1 \approx 1.1 I_{dc}$$

Further, it follows that  $I_{sq} = K'' I_1$ , where  $K''$  represents the proportional coefficient between  $I_{sq}$  and  $I_1$ . This eventually leads to the relation between the torque  $T_e$  and the DC current as

$$T_e = 1.1 K_c K'' I_{dc} \quad (2.10)$$

### 2.4.6 Rectifier Control

With reference to Fig. 2.12b, the torque control can be achieved through the control of the current  $i_{sq}$ . The generator currents can be controlled as follows:

$$\begin{aligned} v_{sd}^* &= v_{sd} - \omega_r L_s i_{sq} \\ v_{sq}^* &= v_{sq} + \omega_r L_s i_{sd} + \omega_r \Psi_{PM} \end{aligned} \quad (2.11)$$

A good selection of the control variables  $v_{sd}^*$  and  $v_{sq}^*$  leads to a decoupled control of the two current components

$$\begin{aligned} i_{sd} &= \frac{-v_{sd}^*}{sL_s - R_s} \\ i_{sq} &= \frac{-v_{sq}^*}{sL_s - R_s} \end{aligned} \quad (2.12)$$

It follows that the stator  $q$  axis current component is used to control the generator torque, but a freedom degree remains to set DC that can be used for flux weakening [41].

## 2.5 Storage Technologies

Storage is important in the MG both because peak loads are expensive to serve with purchased power and because MG generation sources may not be able to respond to load changes as needed [15]. Load changes are usually caused by short-lived events, such as fast transients resulting from starting of motors or turning on/off of equipment, or from slower changes that exceed the ramping capability of generation available



at any given time. All the storage systems mentioned in the sections below require power electronics to convert the stored power to standard, 60-Hz, AC, utility-grade power. These systems can be designed to switch into operation in subcycle time frames, so they are ideal for tracking fast load changes or immediately providing backup if utility power is lost.

2.5.1 Classification of Electrical Energy Storage

Electrical energy storage (EES) has played three main roles.

- 1. First, EES reduces electricity costs by storing electricity obtained at off-peak times when its price is lower, for use at peak times instead of electricity bought then at higher prices.
- 2. Secondly, in order to improve the reliability of the power supply, EES systems support users when power network failures occur due to natural disasters, for example.
- 3. Their third role is to maintain and improve PQ, frequency and voltage.

A widely used approach for classifying EES systems is the determination according to the form of energy used. In Fig. 2.13, EES systems are classified into mechanical, electrochemical, chemical, electrical, and thermal energy storage (TES) systems. Hydrogen and synthetic natural gas are secondary energy carriers and can be used to store electrical energy via electrolysis of water to produce hydrogen and, in an additional step, methane if required. In fuel cells electricity is generated by oxidizing hydrogen or methane. This combined electrolysis-fuel cell process is an electrochemical EES. However, both gases are multipurpose energy carriers. For example, electricity can be generated in a gas or steam turbine. Consequently,

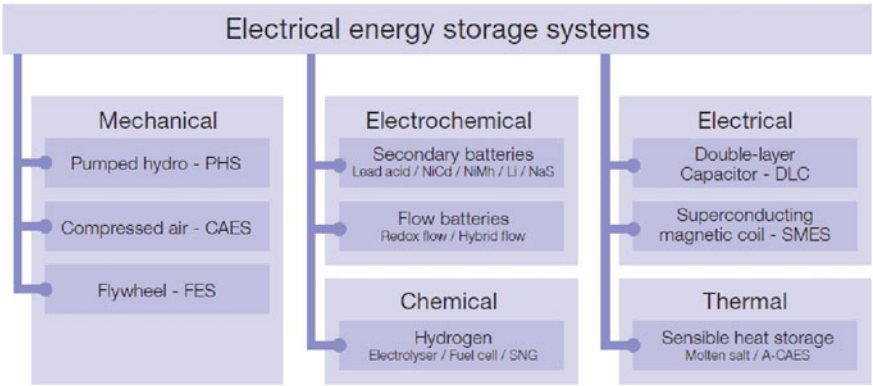


Fig. 2.13 Electrical energy storage

they are classified as chemical energy storage systems. In Fig. 2.13 TES systems are included as well, although in most cases electricity is not the direct input to such storage systems. But with the help of TES the energy from renewable energy sources (RESs) can be buffered and thus electricity can be produced on demand. Examples are hot molten salts in concentrated solar power plants and the storage of heat in compressed air plants using an adiabatic process to gain efficiency.

### ***2.5.2 Mechanical Storage Systems***

The most common mechanical storage systems are pumped hydroelectric power plants (pumped hydro storage), compressed air energy storage, and flywheel energy storage.

- Pumped hydro storage power plants represent nearly 99 % of worldwide installed electrical storage capacity, which is about 3 % of global generation capacity. Conventional pumped hydro storage systems use two water reservoirs at different elevations to pump water during off-peak hours from the lower to the upper reservoir (charging). When required, the water flows back from the upper to the lower reservoir, powering a turbine with a generator to produce electricity (discharging).
- In compressed air (compressed gas) energy storage, air is used as storage medium due to its availability. Electricity is used to compress air and store it in either an underground structure or an aboveground system of vessels or pipes. When needed the compressed air is mixed with natural gas, burned and expanded in a modified GT. Typical underground storage options are caverns, aquifers or abandoned mines.
- In flywheel energy storage rotational energy is stored in an accelerated rotor, a massive rotating cylinder. The main components of a flywheel are the rotating body/cylinder (comprised of a rim attached to a shaft) in a compartment, the bearings and the transmission device (motor/generator mounted onto the stator). The energy is maintained in the flywheel by keeping the rotating body at a constant speed. An increase in the speed results in a higher amount of energy stored. To accelerate the flywheel electricity is supplied by a transmission device. If the flywheel's rotational speed is reduced electricity may be extracted from the system by the same transmission device.

### ***2.5.3 Batteries***

Batteries are the traditional method of storing electrical energy; there is considerable operational experience with battery systems. Lead–acid batteries, available in almost any size, are used in many applications that require backup power. Batteries using other chemistries are now also available commercially. Recent improvements have

increased energy storage density and extended batteries lifetimes. Discharge rates are determined by the batteries design and the chemical reactions used for energy storage.

Batteries store energy in chemical form and are charged/discharged with DC current. This DC current is converted to standard, 60-Hz, AC electrical power by means of power electronics. Most commercial uninterruptible power supplies rely on batteries.

#### ***2.5.4 Flywheels***

Many improvements have been made to flywheel systems in recent years. These systems now incorporate composite rotors, magnetic bearings, and advanced power electronics. Flywheels store energy in high-speed (up to 100,000-rpm) rotating wheel-like rotors or disks connected to motor/generators. High-speed rotation is important because the amount of power stored in the flywheel is proportional to the square of the rotational speed. The flywheel is charged by taking utility power and converting it to drive the flywheel motor, which increases flywheel speed. During a “discharge,” power is drawn from the flywheel by the generator, which slows the rotor speed. Because the output of the flywheel generator is variable, an inverter is used to convert power to standard, 60-Hz or 50-Hz AC power.

Flywheel systems come in a wide range of sizes with differing discharge rates for different amounts of time. The flywheel stores a fixed amount of energy (kWh). It can be discharged at high power (kW) for a short time or at a slower rate for a longer period. Flywheels contain no hazardous materials and are not affected by temperature extremes as batteries are, but flywheels are costly and cannot store energy indefinitely.

#### ***2.5.5 Superconducting Magnetic Energy Storage***

Superconductors allow the passage of electrical current without losses. Electrical energy is stored as a circulating current in a superconducting coil of wire. This circulating current establishes a magnetic field in which the energy is stored. The major energy loss in this system results from the need to cool the coil to very low temperatures. PEIs charge and discharge the superconducting coil. Most commercial systems are somewhat larger than 250kW in capacity. Superconductor storage technology could be adapted to larger MG applications.

### 2.5.6 Supercapacitors

Supercapacitors are very-high-capacity electrolytic devices that store energy in the form of electrostatic charge. They are composed of two electrodes with a very thin separator. Energy storage capacity increases as the surface area of the electrodes increases. Energy is stored as a DC field in the supercapacitor, and the system uses power electronics to both charge and discharge the capacitors. Supercapacitors can have very high discharge rates and could handle fast load changes in a MG.

## 2.6 Inverter Interfaces

There are two basic classes of microsources:

- DC sources, such as fuel cells, PV cells, and battery storage; and
- variable high-frequency AC sources such as a microturbines, whose output is converted to DC.

In both cases, the DC voltage that is generated needs to be interfaced to the AC network and its loads. Power electronics provide this interface as a converter periodically switches the DC voltage polarity on the AC side to create an AC waveform of desired magnitude and phase.

A basic understanding of power electronics requires understanding of the creation of waveforms of different magnitudes, phases, and frequencies using circuits containing rapidly acting switches and energy storage elements. Power electronic devices are designed to operate like switches, but, because these devices are made of semiconducting materials like silicon, they can function much more rapidly than mechanical switches. Energy storage elements, such as inductors and capacitors, filter the sharp-edged waveforms created by the switching.

### 2.6.1 Voltage Source Inverters

A typical circuit and switching sequence is needed that can convert the DC voltage from a microsource to three-phase AC voltage. Consider the circuit in Fig. 2.14a.

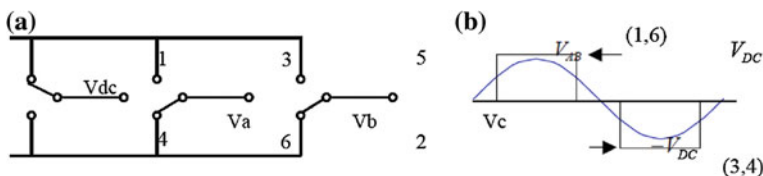


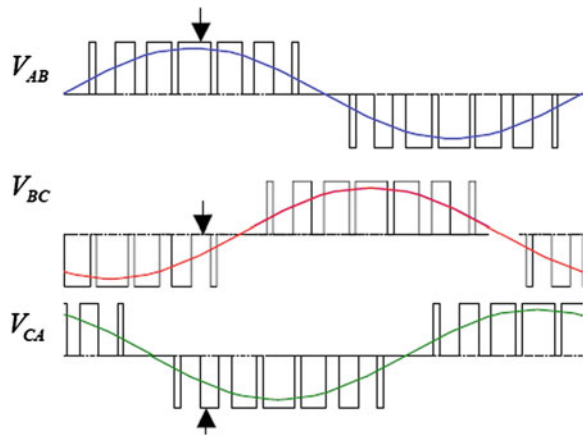
Fig. 2.14 Voltage synthesis. **a** Circuit. **b** Line-to-line voltage

On the left is a DC voltage that is provided by the microsource and connected to a three-phase AC system using double-pole switches. In reality, these switches are power electronic devices with bidirectional current flow capability and rapid switching speeds. In the current positions (1,6,2), the three-phase line-to-line voltage is:  $V_{AB} = V_{DC}$ ,  $V_{BC} = 0$  and  $V_{CA} = V_{DC}$ . This strategy allows the converter to synthesize three AC square waves of voltage at the correct phase to each other. Figure 2.14b shows the VAB synthesized square wave. The positive voltage is achieved by the switch positions shown (1,6); negative voltage requires the opposite (3,4) position.

Although a square wave allows full control of rms voltage output and phase, it would require a great deal of filtering to provide the loads with the required sinusoidal waveforms. Power electronic switching devices have the ability to switch much more rapidly than the fundamental frequency, which means that PWM is an option. For example, for the positive voltage section, Fig. 2.14b, the inverter can rapidly switch from the (1,6) position to the (1,3) or (4,6) position, which provides zero voltage between phases A&B. The same can be done on the negative side. This allows the instantaneous average output to be held closer to the desired fundamental output. A converter incorporating PWM considerably less filtering to achieve the required PQ.

In general, PWM is limited by the switching frequency of the power electronic device and the techniques of the controller. Typical switching frequencies are at least 30 times faster than the fundamental frequency. During each switching period, the inverter control selects the times of conduction or duty cycles that create the desired voltage for that period. The resulting voltage is made of pulses of different widths (hence the name PWM). The pattern and number of pulses are designed to provide the required voltage magnitude, and the pulses are placed to minimize the harmonic content. Such a pattern is shown in Fig. 2.15 for all three phases. The arrows indicate the switch position shown in Fig. 2.14a.

**Fig. 2.15** Three-phase PWM voltage



## 2.6.2 Inverter Realization for Microsources

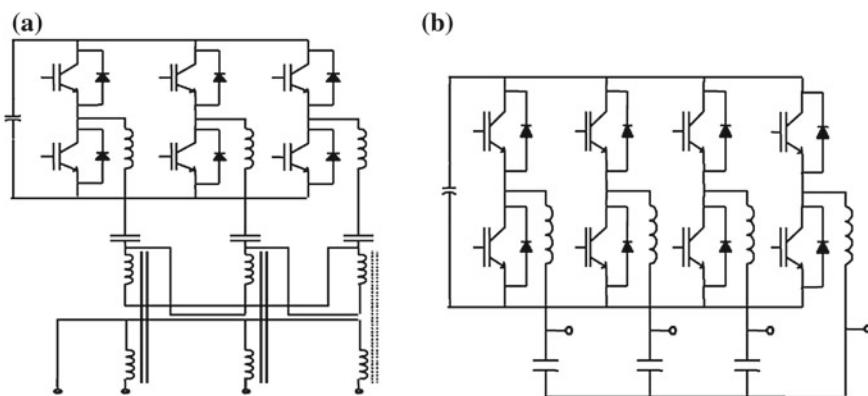
### 2.6.3 Inverter Realization

To realize an actual voltage-sourced inverter (VSI) with PWM, two key issues must be addressed: implementation of switches and connection to the customers AC system. The switches shown in Fig. 2.14 are implemented using insulated gate bipolar junction transistor (IGBT) and diodes. The advantages of IGBTs include their simple gate drives derived from voltage control requirements and their ample voltage/current ratings up to 3,000 V and 1,200 A. Their switching times are less than one microsecond. IGBTs with reverse diodes are shown in place of switches in Fig. 2.16.

Microsources such as microturbines, fuel cells, and PV systems seldom exceed 200 kw and in many cases are smaller than 100 kw. This low level of power along with the need to utilize waste heat means that these sources are placed at the customers site rather than at the utilities substation. AC systems are usually 480 volts or less with a four-wire configuration to accommodate single-phase loads. This requirement can be met using the three-legged inverter shown in Fig. 2.14 with the addition of a star-delta transformer the center point of the star can be used to provide the extra wire (see Fig. 2.16a). Another possibility is to add a fourth leg to provide the extra connection point (see Fig. 2.16b). The operation is similar to one discussed in the section on VSIs above except that the DC voltage is always switched between the neutral and single-phase. This allows for direct creation of phase-to-neutral voltages rather than line-to-line voltage provided by a three-legged inverter.

The differences between the two circuits in Fig. 2.16 include:

- the use of magnetic versus extra IGBTs and diodes, and
- the handling of fault current and dependents between DC and AC voltage levels.



**Fig. 2.16** PWM inverters with four-wire interface, **a** Using star-delta transformer, **b** direct connection using four-legged inverter

During a fault, fault current will be flowing in the four-legged inverter; in transformer-coupled systems, the fault current will circulate in the delta winding. For the transformer-coupled system the DC voltage becomes a free variable because of the turns ratio. In the direct-coupled system the DC voltage needs to be 10–20 percent larger than the required peak AC voltage.

### 2.6.4 Unbalanced AC Voltages

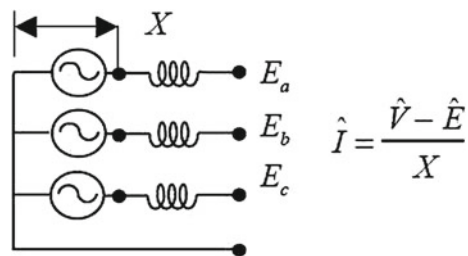
Microsources with AC voltages of 480 V or less and a four-wire configuration to accommodate single-phase loads have unbalanced voltages because of asymmetries in the wiring and the presence of unbalanced loads. When these microsources are connected to the AC system using the inverters discussed above, there will be uneven phase currents. However, microsources may be intolerant of voltage imbalances. Field experience with ONSI fuel cells, for example, has shown that imbalances trip the current protection in the inverter because it assumes balanced currents. (This is the norm for adjustable speed drive protection)

Both inverters shown in Fig. 2.16 can be represented as shown in Fig. 2.17 to demonstrate interactions with the AC system. The VSI creates three AC voltages,  $V_{a,b,c}^{inverter}$  that are coupled to the AC system through three inductors,  $X$ . The current that flows in each inductor is dependent on the inverter and AC system voltages. If the AC system voltages are balanced and the inverter creates balanced voltages, the currents are equal. When the AC system voltages are unbalanced, the currents also become unbalanced. The inverter has the flexibility to create unbalanced voltages between phases that can:

- Rebalance the output currents,
- Correct the systems voltage imbalance,
- Regulate the positive sequence AC voltage but not correct for the imbalance, and
- Remove the negative sequence AC voltage component that results from a voltage dip.

In general, VSIs have the flexibility to deal with most unbalanced situations seen in the field, but this flexibility is not currently used. The Honeywell Parallon 75 uses the system shown in Fig. 2.16a. It can control power and reactive power flow.

**Fig. 2.17** Basic four-wire source



In situations where AC voltages are unbalanced, the currents are also unbalanced and will trip at 20% overcurrent in the delta winding. The Capstone 330 uses the system in Fig. 2.16b. In island mode, the unit provides balanced three-phase system voltages. The currents are a function of the load imbalance, and the system trips when the neutral line has a power flow above one-third of the systems power rating. For highly unbalanced loads, the total output could be less than one-third the rating of the microturbine.

## 2.7 Conclusions

This chapter paves the way to discuss numerous concepts pertaining to DG plants. The first section aims to provide a complete overview of the main control issues in small WT systems. The overall system is analyzed both on wind source-side and on grid-side, focusing on the main power converters configurations. Looking at the source-side, it results that the most critical issues are: sensorless operation of the generator and power limitation. Sensorless operation can be based on a PLL, but special care is required in the design since when the converter starts to switch it produces a voltage at the point of connection of the PMSG and the PLL gets synchronized with it, as a consequence an error in the rotor position occurs and it should be estimated and properly compensated. About power limitation, it is highlighted that two systems for limiting the power in excess, one mechanical (the pitch controller) and the other one electrical (the braking chopper), may interact. In fact, in small power WT systems their time constants can be similar and the controller should be properly designed.

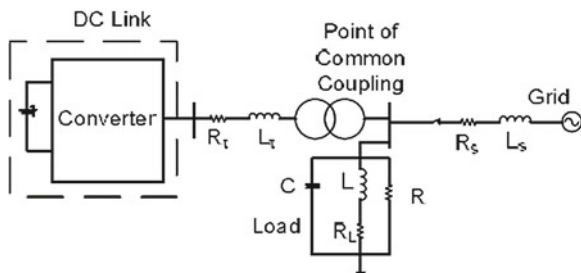
## 2.8 Suggested Problems

In the following set of problems, reference is made to the generic prototype of wireless networked control system (WNCS) depicted.

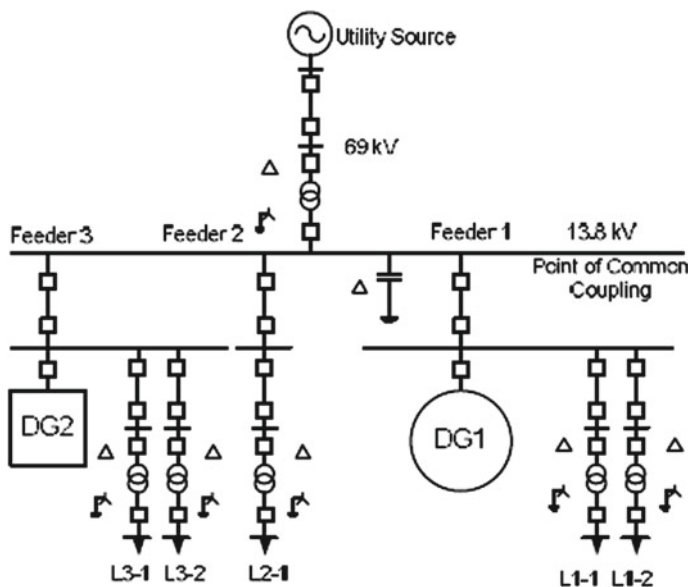
**Problem 2.1** MG dynamics are studied in the island mode. The MG consists of a single inverter-interface DG and a single load connected to the point of common coupling (PCC). The DG model involves a constant voltage source, a power electronic converter, a transformer and a filter. In Fig. 2.18, the load is modeled as an RLC circuit. Investigate a possible control strategy subsequent to an islanding event.

**Problem 2.2** Consider Fig. 2.19 which gives comprehensive MG model including both the SYGN-based DGs as well as power electronics-interfaced DGs with the associated controllers. Develop a small signal model of such a model and examine the eigenvalues and participation factors, low frequency electromechanical oscillations and high-frequency modes. Carry out a sensitivity analysis for different operating points.



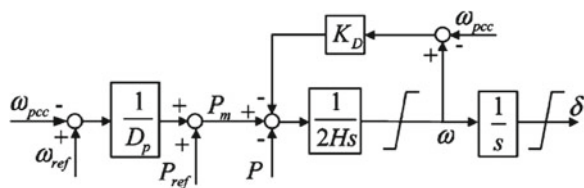


**Fig. 2.18** A dynamic model of microgrid



**Fig. 2.19** Microgrid circuit diagram

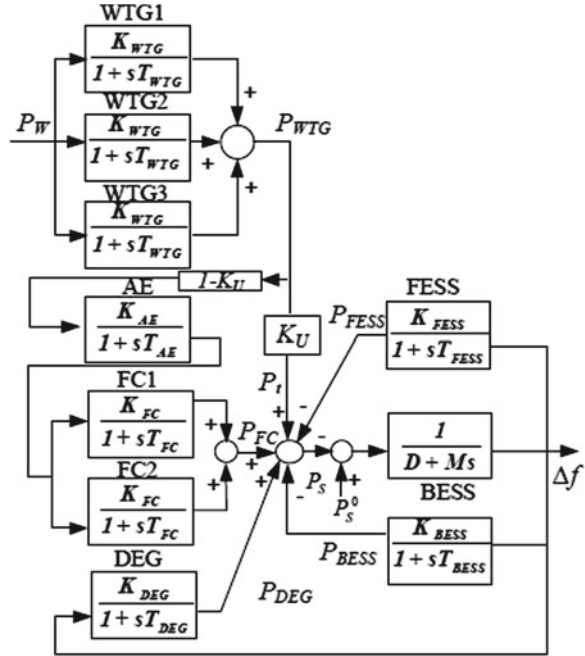
**Fig. 2.20** Microgrid frequency control diagram



Next consider Fig. 2.20 for a prescribed frequency control of MGs including an oscillator generates reference frequency. Investigate the droop mechanism for the frequency control.

Use the following data for numerical simulation:

**Fig. 2.21** A microgrid dynamic model



**Problem 2.3** Dynamics of several DGs such as PV units, WTs, fuel cells, flywheel, battery storage, and diesel generator are approximated by a first order linearized model with a time constant and a gain factor as shown in Fig. 2.21. The studied system is operated in the island mode while the network is neglected. Battery storage, flywheel, and the diesel generator adjust their settings according to the changes in MG frequency. Conduct a small signal stability analysis for such a system and explore the impact of power-frequency (PF) droops (Table 2.1).

**Problem 2.4** Consider the detailed MG model presented in Fig. 2.22. It must be noted that each DG supplies its load which can be unbalanced or nonlinear, where the DGs are converter-based. A common balanced load is also supplied by the DGs. Figure 2.23 shows the model used for the converter. Discuss a possible control strategy for load sharing among DGs while maintaining PQ in both the grid-connected and island modes.

**Problem 2.5** The power droop control has a long history of use for the SYGN control in power system. It has been recently used for parallel inverter control and especially in inverter-dominated MG. Let  $E_i$  and  $V$  be the amplitudes of the  $i$ th inverter output voltage, and PCC voltage respectively.  $\varphi_i$  is the power angle.  $R_i$  and  $X_i$  are the resistance and inductance of the line impedance. Consider Fig. 2.24, derive expressions for the inverter output active  $P_i$  and reactive power  $Q_i$ . Use sensitivity



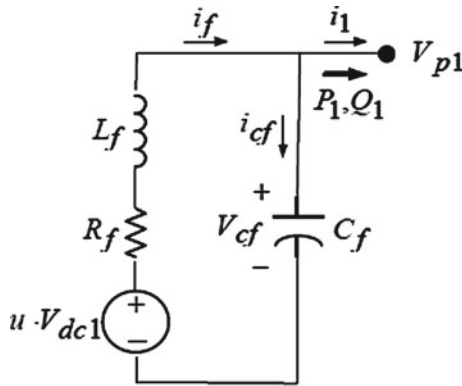


Fig. 2.23 One phase of convertor model

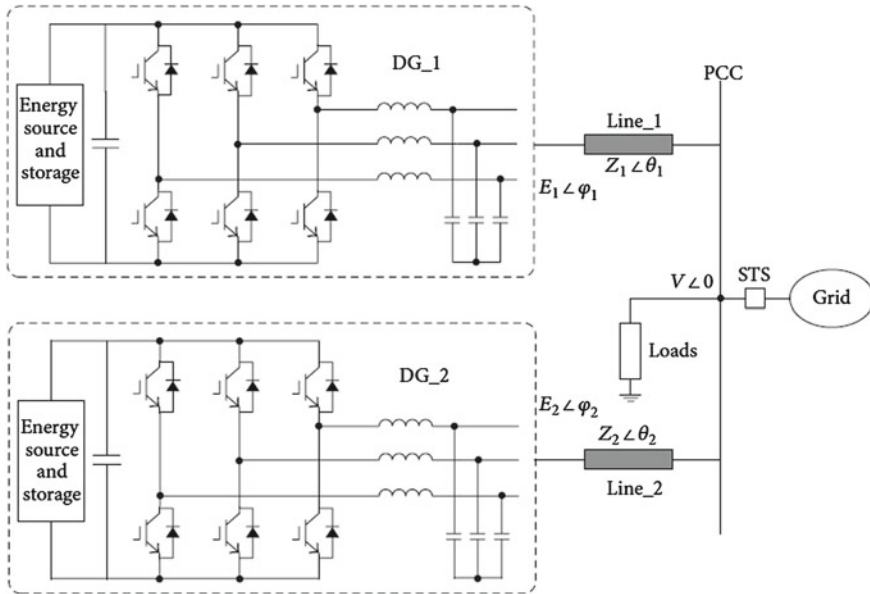


Fig. 2.24 A schematic of an inverter-based microgrid

When the switch is closed, the system is said to be in grid mode. In this mode, the microsources act as constant power sources, which are controlled to inject the demanded power into the network. The interfaced DG needs to be properly controlled in order to provide the required active and reactive power to ensure the system stability for which the active and reactive power control (PQ control) technique is designed. When the switch is opened, the system is said to be in islanded mode. When a fault occurs or for maintenance purpose main grid need to be disconnected from the MG.

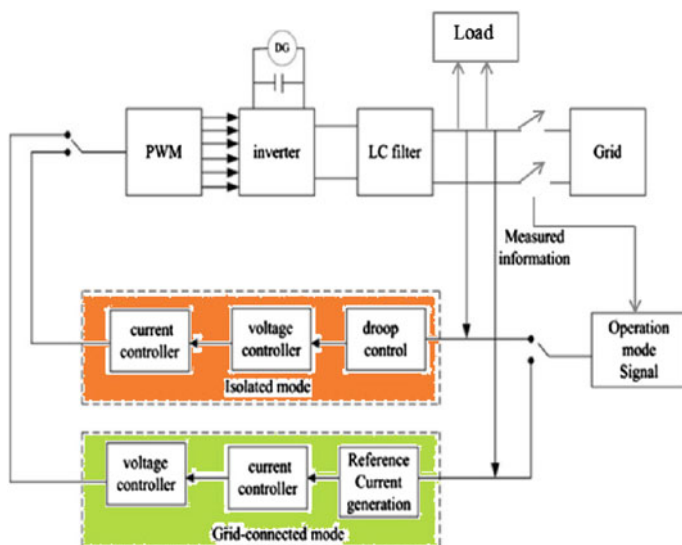


Fig. 2.25 Grid-connected system

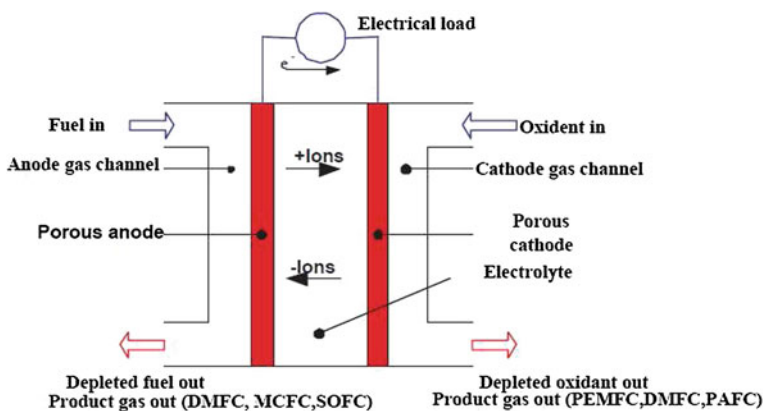


Fig. 2.26 Fuel cell system

MG thus has to provide an uninterrupted power to the loads. Give a representative analysis of the system.

**Problem 2.7** The proposed system configuration, as shown in Fig. 2.26, incorporates a particular fuel cell system.

Develop an appropriate dynamic model.

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