DISTRIBUTED GENERATION

Study and comparison of different types of distributed generation

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Abstract

As a result of the application of deregulation in the electric power sector, a new identity appeared in the electric power system map known as “distributed generation” (DG). According to new technology, the electric power generation trend uses disbursed generator sized from kW to MWat load sits instead of using traditional centralized generation units sized from ١٠٠MW to GW and located far from the loads where the natural recourses are available. This paper introduces a survey of this

revolutionary approach of DGs, which will change the way electric power systems operate along with their types and operating technologies. Some important definitions of DGs and their operational constraints are discussed to help in understanding the concepts and regulations related to DGs. Furthermore, we will survey the operational and economical benefits of implementing DG sin the distribution network. Most DG literatures are based on studying the definitions, constructions or benefits of DGs separately. However, in our paper we aim to give a comprehensive survey by adding new classifications to relate the DG types, technologies and applications to each other**.**

List of abbreviation

Distributed generation (DG);
Fuel cell (FC);
Micro-turbine (MT);
Photovoltaic (PV);
Wind turbine (WT)

Fixed speed induction generator (FSIG)
doubly fed induction generator (DFIG)

Aim of the project

Distributed generation, unlike traditional generation, aims to generate part of required electrical energy on small scale closer to the places of consumption and interchanges the electrical power with the network.

It represents a change in the paradigm of electrical energy generation.

The distributed generation, also termed as embedded generation or dispersed generation or decentralized generation, has been defined as electric power source connected directly to the distribution network or on the customer site of the meter).

The emergence of new technological alternatives allows the DG technologies in distribution network to achieve immense technical, economical and environmental benefits).

These benefits could be maximized by proper planning i.e. placement of DGs at optimum locations with optimum size and suitable type.

Chapter one - distributed generation

١,١ Introduction

Small scale generating technologies (e.g. solar, wind, CHP, hydro or newer technologies) that are connected to the electric power grid are identified as Distributed Generation (DG).

DG systems allow customers to produce some or all of the electricity they need.

The electricity a customer uses (e.g. for HVAC, consumer electronics, lights) is their electric load.

By generating a portion or all of the electricity a customer uses, the customer can effectively reduce their electric load.

In general, DG systems produce power for the buildings which the systems are connected to (e.g. solar panels on a home or business).

Renewable DG systems are able to provide power with minimal impact on the environment.

However, most renewable DG systems only produce power when their energy source, such as wind or sunlight, is available.

Due to the intermittency of the power supply from DG systems, there may be times when the customer needs to receive electricity from the utility company's electric grid. When a DG system produces more power than the customer's load, excess power is sent back to the utility company's electric grid. This reduces the overall load that the utility company needs to supply.

DG systems allow customers to be powered by their own electric generation systems, rather than by traditional central power plants (e.g. coal and nuclear).

Also, customers are able to be compensated for reducing the load on the grid through the net metering program or by contract.

When installing DG systems, customers are required to work with their local utility company.

To benefit from DG systems,

customers must comply with the interconnection tariff and follow the interconnection process.

The interconnection tariff details the regulations, conditions, and time frames associated with the interconnection process, which ensures that the newly connected DG systems will have no adverse impacts on safety, reliability, and power quality of the utility’s electric grid.

١.٢ About Distributed Generation

Distributed generation refers to a variety of technologies that generate electricity at or near where it will be used, such as solar panels and combined heat and power.

Distributed generation may serve a single structure, such as a home or business, or it may be part of a microgrid (a smaller grid that is also tied into the larger electricity delivery system), such as at a major industrial facility, a military base, or a large college campus.

When connected to the electric utility’s lower voltage distribution lines, distributed generation can help support delivery of clean, reliable power to additional customers and reduce electricity losses along transmission and distribution lines.

In the residential sector, common distributed generation systems include: (Solar photovoltaic panels , Small wind turbines , Natural-gas-fired fuel cells , Emergency backup generators, usually fueled by gasoline or diesel fuel) In the commercial and industrial sectors, distributed generation can include resources such as: Combined heat and power systems, Solar photovoltaic panels, Wind, Hydropower, Biomass combustion or cofiring, Municipal solid waste incineration, Fuel cells fired by natural gas or biomass, Reciprocating combustion engines, including backup generators, which are may be fueled by oil.[١]

١.٣ Reasons for distributed generation

The conventional arrangement of a modern large power system (illustrated in Figure ١،١) has a number of advantages.

Large generating units can be made efficient and operated with only a relatively small staff.

The interconnected high voltage transmission network allows the most efficient generating plant to be dispatched at any time, bulk power to be transported large distances with limited electrical losses and generation reserve to be minimized.

The distribution networks can be designed simply for uni-directional flows of power and sized to accommodate customer loads only.

However, particularly in response to climate change, many governments have set ambitious targets to increase the use of renewable energy and to reduce greenhouse gas emissions from electricity generation.

Examples of these policy initiatives include the ٢٠٠٧ European Union requirement to provide ٢٠٪ of all energy used in Europe from renewable sources by ٢٠٢٠ and the California Renewable Portfolio Standard that calls for ٣٣٪ of electrical energy to be from renewables by the same year.

More radically, many climate scientists and policymakers in developed countries consider that an ٨٠٪ reduction in greenhouse gas emissions by ٢٠٥٠ is necessary if average global temperature rises of more than ٢°C are to be avoided.

The electrical power sector is seen as offering an easier and more immediate opportunity to reduce greenhouse gas emission than, for example, road or air transport and so is likely to bear a large share of any emission reductions.

The UK share of the European Union target is only ١٥٪ of all energy to come from renewables by ٢٠٢٠ but this translates into some ٣٥٪ of electrical energy.

This target, set in terms of annual electrical energy, will result at times in very large fractions of instantaneous electrical power being supplied from renewables, perhaps up to ٦٠–٧٠٪. Most governments have financial mechanisms to encourage the development of renewable energy generation with opinion divided as to whether feed-in-tariffs, quota requirements (such as the UK Renewables Obligation), carbon trading or carbon taxes provide the most cost-effective approach, particularly for the stimulus of emerging renewable energy technologies.

Established technologies include wind power, micro-hydro, solar photovoltaic systems, landfill gas, energy from municipal waste, biomass and geothermal generation.

Emerging technologies include tidal stream, wave-power and solar thermal generation.

Renewable energy sources have a much lower energy density than fossil fuels and so the generation plants are smaller and geographically widely spread.

For example wind farms must be located in windy areas, while biomass plants are usually of limited size due to the cost of transporting fuel with relatively low energy density.

These smaller plants, typically of less than ٥٠–١٠٠ MW in capacity, are then connected into the distribution system.

It is neither cost-effective nor environmentally acceptable to build dedicated electrical circuits for the collection of this power, and so existing distribution circuits that were designed to supply customers' load are utilized.

In many countries the renewable generation plants are not planned by the utility but are developed by entrepreneurs and are not centrally dispatched but generate whenever the energy source is available.

Cogeneration or combined heat and power (CHP) schemes make use of the waste heat of thermal generating plant for either industrial process or space heating and are a well-established way of increasing overall energy efficiency.

Transporting the low temperature waste heat from thermal generation plants over long distances is not economic and so it is necessary to locate the CHP plant close to the heat load.

This again leads to relatively small generation units, geographically distributed and with their electrical connection made to the distribution network.

Although CHP units can, in principle, be centrally dispatched, they tend to be operated in response to the heat requirement or the electrical load of the host installation rather than the needs of the public electricity supply system.

Micro-CHP devices are intended to replace gas heating boilers in domestic houses and, using Stirling or other heat engines, provide both heat and electrical energy for the dwelling.

They are operated in response to the demand for heat and hot water within the dwelling and produce modest amounts of electrical energy that is used to offset the consumption within the house.

The electrical generator is, of course, connected to the distribution network and can supply electricity back to the network, but financially this is often unattractive with low rates being offered for electricity exported by micro-generators.

The commercial structure of the electricity supply industry plays an important role in the development of distributed generation.
In general a deregulated environment and open access to the distribution network is likely to provide greater opportunities for distributed generation although early experience in Denmark provided an interesting counter-example where both wind power and CHP were widely developed within a vertically integrated power system.[٢]

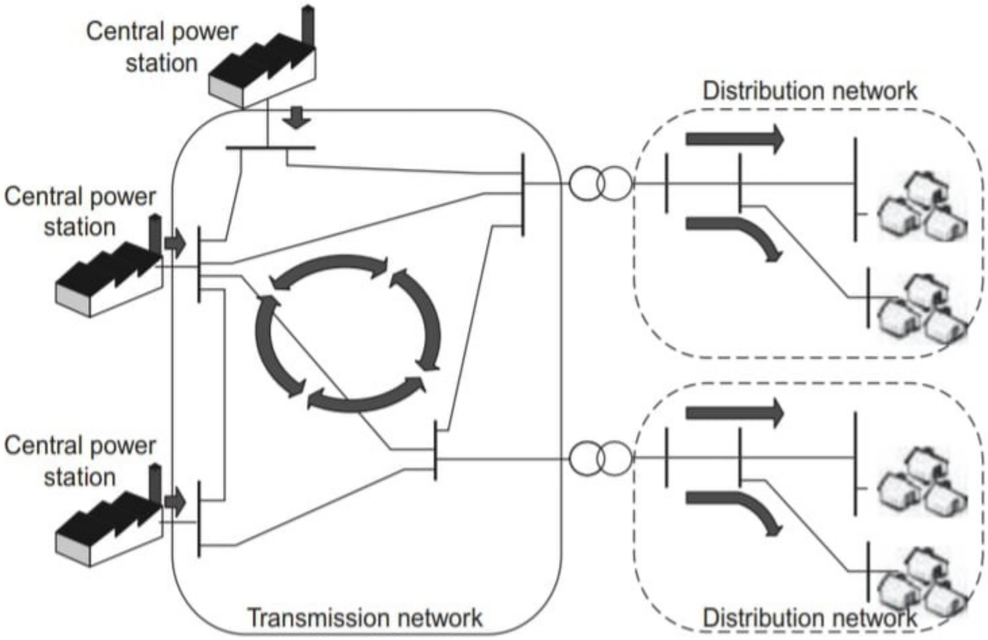


Figure 1.1 Conventional large electric power system

١.٤ The future development of distributed generation

At present, distributed generation is seen primarily as a means of producing electrical energy and making a limited contribution to the other ancillary services that are required in any power system.

Although this is partly due to the technical characteristics of the plant, this restricted role is predominantly caused by the administrative and commercial arrangements under which distributed generation presently operates and is rewarded, i.e. as a source of energy.

This is now changing with the transmission connection requirements (the so-called Grid Codes) that specify the performance required from renewable generation connected to transmission networks being applied increasingly to larger distributed generation schemes.

Levels of penetration of distributed and renewable generation in some countries are such that it is already beginning to cause operational problems for the power system.

Difficulties have been reported in Denmark, Germany and Spain, all of which have high penetration levels of renewables and distributed generation.

This is because, thus far, the emphasis has been on connecting distributed generation to the network in order to accelerate the deployment of all forms of distributed energy resources rather than integrating it into the overall operation of the power system.

The current policies of connecting distributed generation are generally based on a ‘fit-and-forget’ approach.

This is consistent with historic design and operation of passive distribution networks but leads to inefficient and costly investment in distribution infrastructure.

Traditionally the distribution network has been designed to allow any combination of load (and distributed generation) to occur simultaneously and still supply electricity to customers with an acceptable power quality.

Moreover with passive network operation and simple local generator controls, distributed generation can only displace the energy produced by central generation but cannot displace its capacity as system control and security must continue to be provided by central generation.

We are now entering an era where this approach is beginning to restrict the deployment of distributed generation and increase the costs of investment and operation as well as undermine the integrity and security of the power system.

Hence, distributed generation must take over some of the responsibilities from large conventional power plants and provide the flexibility and controllability necessary to support secure system operation.

Although transmission system operators have historically been responsible for power system security, the integration of ٨ Distributed generation distributed generation will require distribution system operators to develop Active Network Management in order to participate in the provision of system security.

This represents a shift from the traditional central control philosophy, presently used to control typically hundreds of generators to a new distributed control paradigm applicable for operation of hundreds of thousands of generators and controllable loads. Figure ١,٤ shows a schematic representation of the capacities (and hence cost) of distribution and transmission networks as well as central generation of today's system and its future development under two alternative scenarios both with increased penetration of distributed energy resources.

Business as Usual (BaU) represents traditional system development characterized by centralized control and passive distribution networks as of today.

The alternative using SmartGrid concepts and technologies represents the system capacities with distributed generation and the demand side fully integrated into power system operation.[٢]

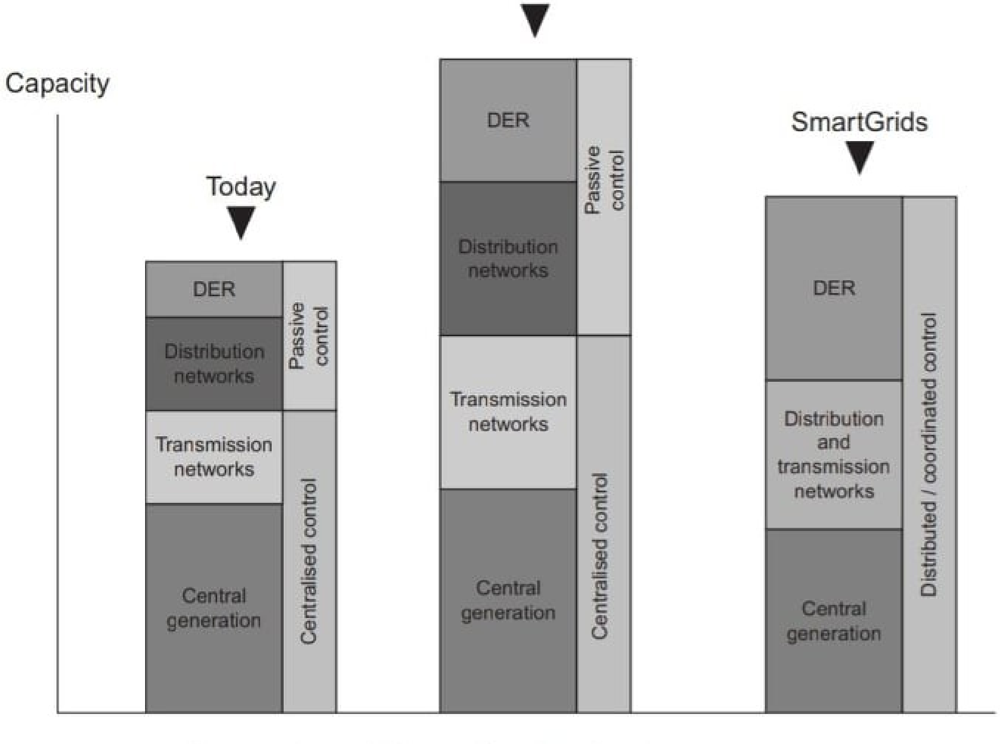


Figure ١,٢ relative levels of system capacity

١.٥ Literature review of the future growth of DG

Distributed generation (DG) is not a new concept but it is an emerging approach for providing electric power in the heart of the power system. It mainly depends upon the installation and operation of a portfolio of small size, compact, and clean electric power generating units at or near an electrical load (customer).

Till now, not all DG technologies and types are economic, clean or reliable. Some literature studies delineating the future growth of DGs are:

- The Public Services Electric and Gas Company (PSE&G), New Jersey, started to participate in fuel cells (FCs) and photovoltaics (PVs) from ١٩٧٠ and micro-turbines (MTs) from ١٩٩٥ till now. PSE&G becomes the distributor of Honeywell's ٧٥kW MTs in USA and Canada. Fuel cells are now available in units range ٣–٢٥٠kW size [٣].

• The Electric Power Research Institutes (EPRI) study shows that by ٢٠١٠, DGs will take nearly ٢٥٪ of the new future electric generation, while a National Gas Foundation study indicated that it would be around ٣٠٪ [٤]

• PV industries and companies expect about one million rooftops equipped by PV modules within the coming decade [٥]. •
The largest commercial ١MW FC (five ٢٠٠kW units) installed by the US Postal Service at the Anchorage Mail Processing Center, Alaska and is connected to the utility grid [٦].

• In the year ٢٠٠٠, new wind farms of ٣٠٠٠MW capacities were installed [٥]. Surveying DG concepts may include DG definitions, technologies, applications, sizes, locations, DG practical and operational limitations, and their impact on system operation and the existing protective devices. This paper focuses on surveying different DG types, technologies, definitions, their operational constraints and operational and economical benefits. Furthermore, we aim to present a critical survey by proposing new DG classifications.

Chapter two

types of distributed generation

There are different types of DGs from the constructional and technological points of view as shown in Fig. ٢.١.

These types of DGs must be compared to each other to help in taking the decision with regard to which kind is more suitable to be chosen in different situations.

However, in our paper we are concerned with the technologies and types of the new emerging DGs: micro-turbines and fuel cells.

The different kinds of distributed generation are discussed below.

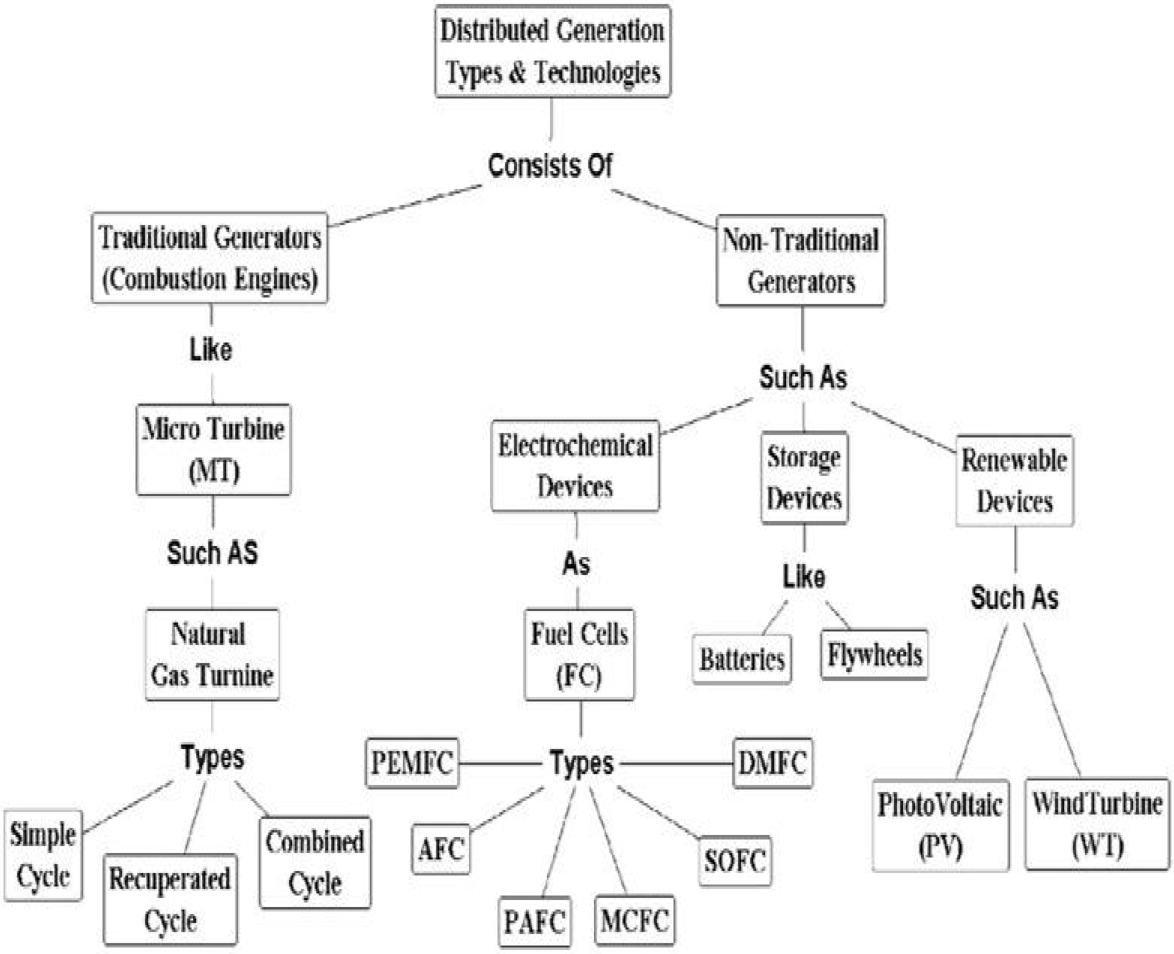


Fig. ٢.١ Distributed generation types and technology.

٢,١ traditional combustion generator

٢,١,١. Micro-turbine (MT)

Micro-turbine technologies are expected to have a bright future.
They are small capacity combustion turbines, which can operate using natural gas, propane, and fuel oil. In a simple form, they consist of a compressor, combustor, recuperator, small turbine, and generator. Sometimes, they have only one moving shaft, and use air or oil for lubrication. MTs are small scale of ٠,٤–١m^٣ in volume and ٢٠–٥٠٠kW in size.
Unlike the traditional combustion turbines, MTs run at less temperature and pressure and faster speed (١٠٠،٠٠٠rpm), which sometimes require no gearbox [٧].
Some existing commercial examples have low costs, good reliability, fast speed with air foil bearings ratings range of ٣٠–٧٥kW are installed in North-eastern US and Eastern Canada and Argentina by Honeywell Company [٣] and ٣٠–٥٠kW for Capstone and Allison/GE companies, respectively [٨].
Another example is ABB MT: of size ١٠٠kW, which runs at maximum power with a speed of ٧٠،٠٠٠rpm and has one shaft with no gearbox where the turbine, compressor, and a special designed high speed generator are on the same shaft [٧].

٢,١,١,١. Advantages of MTs.

- They can be installed on-site especially if there are space limitations. Also they are compact in size and light in weight with respect to traditional combustion engines.
- They are very efficient (more than ٨٠٪) and have lower emissions (less than ١٠ppm NOx) with respect to large scale ones.
- They have well-known technology and they can start-up easily, have good load tracking characteristics and require less maintenance due their simple design [٧].
- They have lower electricity costs and lower capital costs than any other DG technology costs [٣].
- They have a small number of moving parts with small inertia not like a large gas turbine with large inertia.
- Modern power electronic interface between the MT and the load or grid increases its flexibility to be controlled efficiently [٨].

There are different types of MTs according to their operation such as gas turbines and combustion turbines.

Gas turbines are combustion turbines that produce high temperature and pressure gas. This high-pressure gas is used to rotate turbine shaft, which drives a compressor, an electric alternator and generator. Gas turbines are always used above ١MW, but nowadays we can generate electricity through small modulars with a micro-gas turbine of ٢٠٠kW size [٧].

The produced heat can be used as a waste heat recovery to generate steam for compound heat and power (CHP) as shown in Fig. ٢.٢ , combined cycle application and fuel cell/turbine hybrids applications.

MTtypes are different according to their operating cycle configurations [٩].

Simple-cycle gas turbines: Simple gas turbines can be either a single-shaft machine (with air compressor and power turbine (PT) on the same shaft) or a split-shaft machine. Also, they have a burner or combustor, and an electric generator rotated by power turbine.

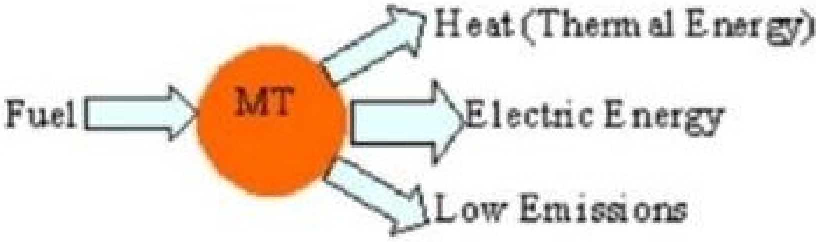


Fig. ٢,٢ Typical micro-turbine operation

Recuperated gas turbines:

They are similar to simple-cycle gas turbines, but with a special heat exchanger (a recuperator).

This recuperator uses the output exhaust thermal energy to preheat compressed air in its pass to the burner to increase the turbine electrical efficiency.

Combined cycle gas turbine:

They use the exhaust energy in a heat recovery steam generator (HRSG)based on the concept of heat recovery, which may include a burner to increase the steam output. Steam from the HRSG drives a steam turbine, which generates power in addition to the main power turbine as shown in Fig.٢.٣ to increase the total electric efficiency.

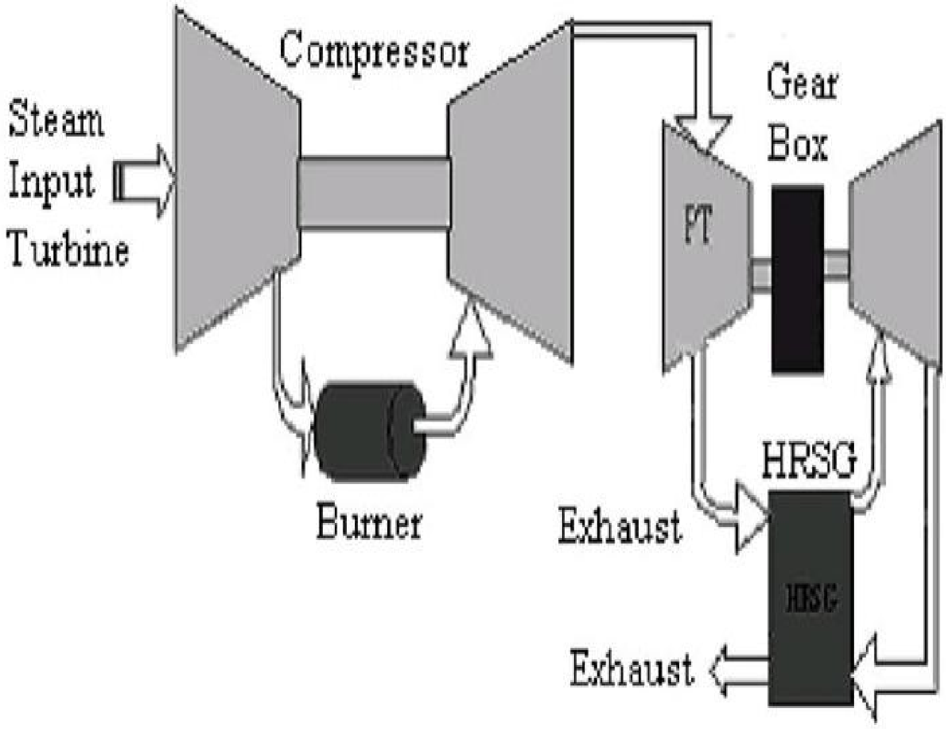


Fig. ٢،٣ Combined cycle gas turbine.

٢,٢. Non-traditional generators

٢,٢,١. Electrochemical devices: fuel cell (FC)

fuel cell (FC) The fuel cell is a device used to generate electric power and provide thermal energy from chemical energy through electrochemical processes.

It can be considered as a battery supplying electric energy as long as its fuels are continued to supply.

Unlike batteries, FC does not need to be charged for the consumed materials during the electrochemical process since these materials are continuously supplied [١٠].

FC is a well-known technology from the early ١٩٦٠s when they were used in the Modulated States Space Program and many automobile industry companies. Later in ١٩٩٧, the US Department of Energy tested gasoline fuel for FC to study its availability for generating electric power [٨].

FC capacities vary from kW to MW for portable and stationary units, respectively.

It provides clean power and heat for several applications by using gaseous and liquid fuels [١١].

FCs can use a variety of hydrogen-rich fuels such as natural gas, gasoline, biogas or propane [١٢].

FCs operate at different pressures and temperatures which varies from atmospheric to hundreds of atmospheric pressure and from ٢٠ to ٢٠٠٠°C, respectively [١٢].

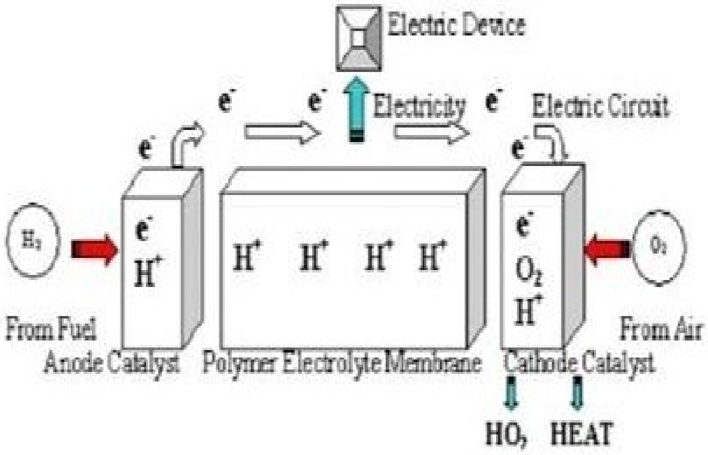


Fig. ٢,٤ Polymer electrolyte membrane FC.

As shown in Fig.٢.٤, a typical FC consists of two oxidant electrodes separated by an electrolyte member.

Oxygen, as an oxidant, passes through one electrode (cathode) either at low pressure (using a blower) or at high pressure (using air compressor) [١٠].

Hydrogen, as a fuel, passes through the other electrode (anode).

FC technology is based on an electrochemical process in which hydrogen and oxygen are combined to produce electricity without combustion.

The catalyst splits the hydrogen atom into a proton and an electron.

The proton passes through the electrolyte, however, electrons create a separate current that can be utilized before they return to the cathode, to be demodulated with the hydrogen and oxygen in a molecule of water [١٠،١١].

The operating stages and products of this electrochemical process, as shown in Fig.٢.٥, are direct current electric power, water, heat, and some low emitted gases (like NOx and CO٢) with respect to traditional generators and hence is considered an environmentally safe electric power generation [١١].

A fuel processor is used to convert the source fuel to a hydrogen-rich fuel stream, which is needed for the electrochemical reaction.

A power electronic device(a power conditioner) has to be used to convert the output direct current to the alternating one to be connected to the grid and control its voltage level according to the required application [١٠،١١].

The hydrogen used can be obtained either by reformation of hydrocarbons or by means of chemical and electrolysis operations from water [١٢].

The most commonly used method is reformation of hydrocarbons such as natural gas because it is already commercially available as it can be transmitted by means of pipelines.

Producing hydrogen can be done chemically by using steam on heated carbon.

The output products of this process are H٢ and CO٢. This chemical operation requires heating for the steam and the carbon, which is considered a waste of energy. Another means of producing H٢,

and storing the energy in it, is from electrolysis of water. This process is not economic as it uses electric energy to do the process and cover its losses [١٢].
Usually the reforming process, which is known as “steam catalytic reforming process” to get a hydrogen-rich fuel [١٣], occurs at high temperature around ٨٠٠◦C. Therefore, we need an external reformer device for low temperature operating FC as shown in Fig.٢.٥ [١٠،١١].

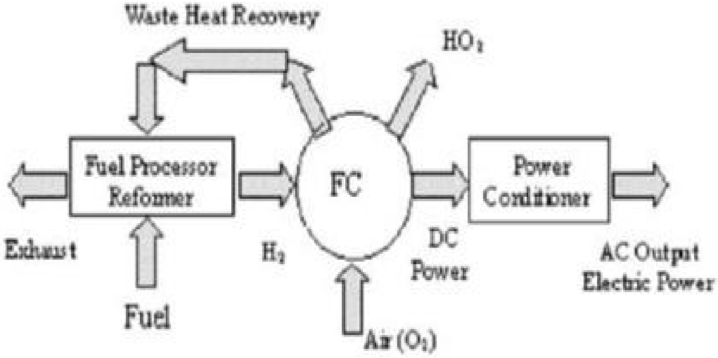


Fig. ٢,٥ FC construction, operation, and products.

٢,٢,١,١. Advantages of FCs.

- FCs transform the fuel chemical energy to electric power with a ٦٠٪ efficiency, which is considered to be twice of that of the traditional generating stations [١٣].
- The absence of moving parts in FCs operation, except for air blowers (for O٢) and fuel (for H٢) and/or water pumps, results in very low noise levels, relatively higher efficiencies and emits lower air pollutants [١١,١٣].
- No combustion is involved in the FC operation make it environmental friendly generation with approximately negligible emissions (low CO٢) [١١].

- Also ,due to the output bi-product (electricity and heat as a result of high fuel conversion efficiency) and their prices, small size FCs in the coming recent years are expected to be implemented in commercial and residential buildings for both purposes of lighting and heating at the same time [١١,١٢].
- Today, FCs consist of staking cells, which give it the flexibility to be built to match specific power needed with less capital cost. FC power plants are commercially available for use by electric power producers and industrial applications [١٢].

٢,٢,٢. Storage devices:

It consists of batteries, flywheels, and other devices, which are charged during low load demand and used when required.

It is usually combined with other kinds of DG types to supply the required peak load demand [٨].

These batteries are called "deep cycle". Unlike car batteries, "shallow cycle" which will be damaged if they have several times of deep discharging, deep cycle batteries can be charged and discharged a large number of times without any failure or damage.

These batteries have a charging controller for protection from overcharge and over discharge as it disconnects the charging process when the batteries have full charge.

The sizes of these batteries determine the battery discharge period. However, flywheels systems can charge and provide ٧٠٠ kW in ٥s [٨].

٢,٢,٣. Renewable devices:

Green power is a new clean energy from renewable resources like: sun, wind, and water.

Its electricity price is still higher than that of power generated from conventional oil sources.

Some types of renewable resources are discussed below:

٢,٢,٣.١. Photovoltaic (PV):

١. Construction: The basic unit of PV is a cell that may be square or round in shape, made of doped silicon crystal.

Cells are connected to form a module or panel and modules are connected to form an array to generate the required power.

٢. Operation and ratings: Cells absorb solar energy from the sunlight, where the light photons force cell electrons to flow, and convert it to de electricity.

Practically, each cell provides ٢-٤ A according to its size with an output voltage of ٠,٥ V. Normally an array, cells connected in series, provides ١٢ V to charge batteries.

٣. Restrictions: PVs consist of modulars which can be connected to provide a variety of power ranges but on the other hand there are many restrictions:

- It provides low output power.
- The cost of land where PVs installed is expensive (١ acer of land produces ١٥٠kW) [٣].
- It is restricted to certain geographic and weather features [٣].

٢,٢,٣,٢.Wind-turbines (WT):

Wind energy is not a new form it has been used for decades.

A WT consists of a rotor, turbine blades, generator, drive or coupling device, shaft, and the nacelle (the turbine head) that contains the gearbox and the generator drive.

Modern wind turbines can provide clean electricity as individuals or as wind farms.

Wind turbine blades usually are two or three blades each nearly ١٠-٣٠ m long.

Operation. The wind rotates the windmill-like blades, which in turn rotate their attached shaft.

This shaft operates a pump or a generator that produces electricity. Although, the energy characteristics of larger wind turbine farms are closer to the centralized energy sources, small wind turbines (working as modules) can be combined with PV and battery systems to serve area of ٢٥-١٠٠ kW.

٢,٢,٣,٢.١The advantages of wind turbines:.

١.Contribute to clean air (no pollution) unlike the traditional oil fuel that contributes acid rain (from sulphur dioxide or nitrogen oxides) and global warming (from carbon dioxide) to the environment.

٢.Contribute to global safety (non-hazardous or radioactive wastes) unlike nuclear power. .

٣.Future sustainable (lt has no input fuel, just the wind which will not run out by time).

٤.Traditional fuel costs increase with time but wind energy costs decrease with time.

chapter three
Distributed generators and their connection to the system

٣.١ introduction

The connection of distributed generators to the network requires understanding the operation and control of different types of generating plant, and often needs studies to evaluate the performance of the power system with the new generation, under both normal and abnormal operating conditions.

The types of generators used for distributed generation depend on their application and energy source.

For example a small diesel generator set would normally use a synchronous generator while a wind turbine may employ a squirrel-cage induction generator, called a fixed speed induction generator (FSIG) in this book, a doubly fed induction generator (DFIG)
or full power converter (FPC) connected generator.

DC sources or those generating at high frequency such as photovoltaic systems, fuel cells or micro-turbines require a power electronic converter to interface them into the power system.

The performance and characteristics of these different types of power plant differ significantly.

The performance of networks with distributed generation is studied using computer programs:

- load or power-flow programs to evaluate the steady-state voltages at busbars and power flows in circuits.
- fault calculators to determine the fault currents caused by different types of fault.
- stability studies to determine the stability of the power system and/or distributed generators, normally following a fault.

٣.٢ Synchronous generators

Synchronous generators are always used in large conventional power plants.

The principles of operation of synchronous generators is electromagnetic induction if there exist a relative motion between the flux and conductor, then an emf is induced in the conductor.

Large steam turbine generator sets use turbo-alternators consisting of a cylindrical rotor with a single DC winding to give one pair of poles and hence maximum rotational speed (٣٠٠٠ rpm on a ٥٠ Hz system; ٣٦٠٠ rpm on a ٦٠ Hz system).

Hydro generators usually operate at lower speeds, and then use multiple pole generators with a salient-pole rotor.

Smaller engine-driven units also generally use salient-pole generators.

Permanent magnet generators are not commonly found in large generating units, as although higher efficiencies can be achieved, direct control of the rotor magnetic field is not possible.

However, permanent magnet synchronous generators are used in some variable-speed wind turbines and in some microgenerators.

Also, permanent magnet generators can be designed to withstand the mechanical forces of high-speed operation when driven by microturbines.

For power system studies, synchronous generators are represented by a voltage behind an impedance as shown in Figure ٣،١. In this model Xs is the synchronous reactance and R is the stator resistance. The synchronous impedance is then, Zs= R+ jXs. For large generators, R is often neglected

Figure ٣،١ Voltage behind impedance model of a synchronous generator

Figure ٣,٢ shows a simplified representation of a ٥ MW synchronous distributed generator driven by a small steam turbine.
If the short-circuit level at the point of connection (C) is, say, ١٠٠ MVA, with an X/R ratio of, say, ١٠ then the total source impedance on a ١٠٠ MVA base will be approximately
Z=٠,١+j١,٠ pu
and with a realistic value of Xs of ١,٥ pu on the machine rating then, again on ١٠٠ MVA base
Xs =j٣٠ pu

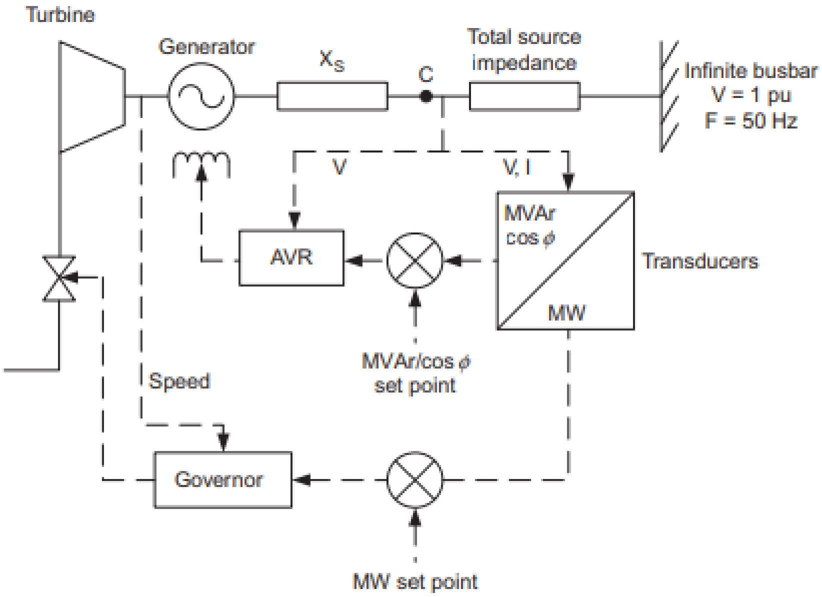


Figure ٣,٢ Control of a synchronous distributed generator

Thus it can be seen immediately that |Xs|>>|Z| and to a first approximation, the synchronous generator will have a very small effect on network voltage (point C).
As a small generator cannot affect the frequency of a large interconnected power system, then the distributed generator can be considered to be connected directly to an infinite busbar.

Figure ٣,٢ is an over-simplification in one important respect in that the other loads on the network are not shown explicitly and these may alter the voltage at the point of connection of the generator considerably.
In some smaller power systems, changes in total system load or outages on the bulk generation system will also cause significant changes in frequency.
conventional method of controlling the output power of a generating unit is to set up the governor on a frequency/power droop characteristic.
This is shown in Figure ٣,٣ where the line (a–b) shows the variation in frequency (typically ٤٪) required to change the power output of the prime mover from no-load to full-load. Thus with ١ per unit (pu) frequency (٥٠ Hz) the set will produce power P١.
If the frequency falls by ١٪ the output power increases to P٣ while if the system frequency rises by ١٪ the output power reduces to P٢.
This, of course, is precisely the behavior required from a large generator that can influence the system frequency, if the frequency drops more power is required while if the frequency rises less power is needed.
The position of the droop line can be changed vertically along the y-axis and so by moving the characteristic to (a' –b') the power output can be restored to P١ even with an increased system frequency or by moving to (a''–b'') for a reduced system frequency.

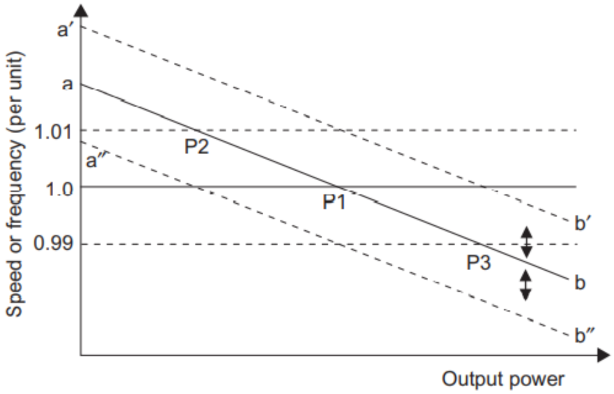


Figure ٣,٣ Conventional governor droop characteristic for generator governor control

A similar characteristic can be set up for voltage control (Figure ٣,٤) with the axes replaced by reactive power and voltage.

Again, consider the droop line (a–b).

At ١ pu voltage no reactive power is exchanged with the system (operating point Q١).

If the network voltage rises by ١٪ then the operating point moves to Q٢ and reactive power is imported by the generator, in an attempt to control the voltage rise.

Similarly if the network voltage drops the operating point moves to Q٣ and reactive power is exported to the system.

Translating the droop lines to (a'–b') or (a''–b'') allows the control to be reset for different condition of the network.

The slope of both the frequency and voltage droop characteristics can also be changed if required.

These frequency and voltage droop characteristics describe simple proportional control systems.

In practice, governor and automatic voltage regulator (AVR) controls are much more complex and will include integral terms to eliminate steady state error. However, the principle remains that this type of controller is intended to control the network variables (i.e. frequency or voltage) and so is appropriate for larger generators.

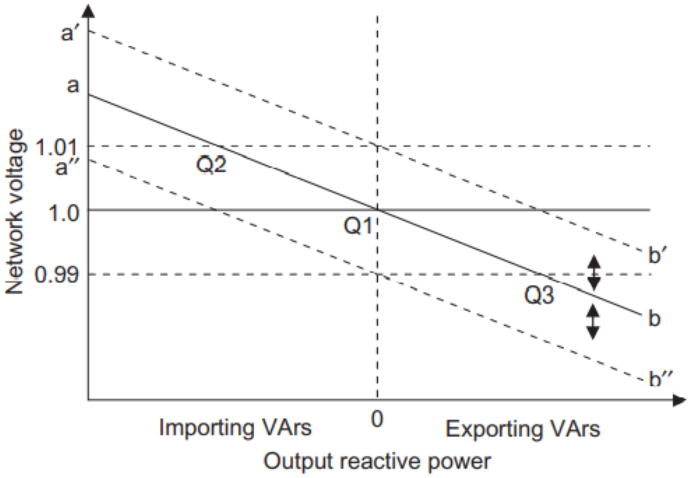


Figure ٣،٤ Quadrature droop characteristic for generator excitation control

These types of control schemes may not be appropriate for small-distributed synchronous generators.

For example an industrial combined heat and power (CHP) plant may wish to operate at a fixed power output, or fixed power exchange with the network, irrespective of system frequency.

Similarly, operation with no reactive power exchange with the network may be desirable in order to minimize reactive power charges.

If the generators are operated on the simple droop characteristics, illustrated in Figures ٣،٣ and ٣،٤, then both real and reactive power outputs of the generator will change constantly as the network frequency and voltage varies due to external influences.

For relatively small synchronous distributed generators on strong networks, control is often based on real and reactive power output rather than on frequency and voltage as might be expected in stand-alone installations or for large generators.

As shown in Figure ٣،٢, voltage and current signals are obtained at the terminals of the generator and passed to transducers to measure the generated real and reactive power output.

The main control variables are MW, for real power, and MVAr or cos Ø for reactive power.

A voltage measurement is also supplied to the AVR and a speed/ frequency measurement to the governor, but these are supplementary signals only.

It may be found convenient to use the MW and MVAr/cos Ø error signals indirectly to translate the droop lines and so maintain some of the benefits of the droop characteristic, at least during network disturbances, but this depends on the internal structure of the AVR and governor.

However, the principal method of control is that, for real power control, the measured (MW) value is compared to a set point and then the error signal fed to the governor which, in turn, controls the steam supply to the turbine.

In a similar manner the generator excitation is controlled to either an MVAr or cos Ø setting.

The measured variable is compared to a set point and the error passed to the AVR and exciter.

The exciter then controls the field current and hence the reactive power output.

It should be noted that the control scheme shown in Figure ٣,٢ pays no attention to the conditions on the power system.

The generator real power output is controlled to a set point irrespective of the frequency of the system, while the reactive power is controlled to a particular MVAr value or power factor irrespective of network voltage.

Clearly for relatively large distributed generators, or groups of smaller distributed generators, which can have an impact on the network this is unsatisfactory and more conventional control schemes that provide voltage support are likely to be appropriate [١٤].

These are well-established techniques used wherever a generator has a significant impact on the power system but there remains the issue of how to influence the owners/operators of distributed generation plant to apply them.

Operating at non-unity power factor increases the electrical losses in the generator while varying real power output in response to network frequency will have implications for the prime mover and steam supply, if it is operated as a CHP plant.

As increasing numbers of small distributed generators are connected to the network it will become important to coordinate their response both to steady-state network conditions and during disturbances.

This requirement for the distributed generation to provide network support is already evident in the transmission network connection Grid Codes that are applied to the connection of large wind farms.

These require that large wind farms operate under voltage control (rather than reactive power or power factor control) to maintain the local voltage particularly during network disturbances and also have the capability of contributing to system frequency response.

It is likely that as distributed generation becomes an ever more significant fraction of the generation on the power system, then such requirements will become more widely applied.

٣,٣ Induction generators:

An induction generator is, in principle, an induction motor with torque applied to the shaft, although there may be some modifications made to the electrical machine design to optimism its performance as a generator. Hence, it consists of an armature winding on the stator, and generally, a squirrel-cage rotor.

Squirrel-cage induction machines are found in a variety of types of small generating plant and are always used in fixed speed wind turbines.

Wound rotor induction machines are used in some specialized distributed generating units particularly with variable slip, where the rotor resistance is varied by an external circuit, and doubly fed variable-speed wind turbines, where the energy flow in or out of the rotor circuit is controlled by power electronics.

The main reason for the use of squirrel-cage induction generators in fixed speed wind turbines is the damping they provide for the drive train (see Figure ٣,٥) although additional benefits include the simplicity and robustness of their construction and the lack of requirement for synchronizing .

The damping is provided by the difference in speed between rotor and the stator magneto motive force (mmf) (the slip speed), but as induction generators increase in size their natural slip decreases [١٥] and so the transient behavior of large induction generators starts to resemble that of synchronous machines. Induction generators have also been used in small hydro sets for many years. Reference [16] describes very clearly basic theory of induction generators and their application in small hydro generators in Scotland in the ١٩٥٠s.

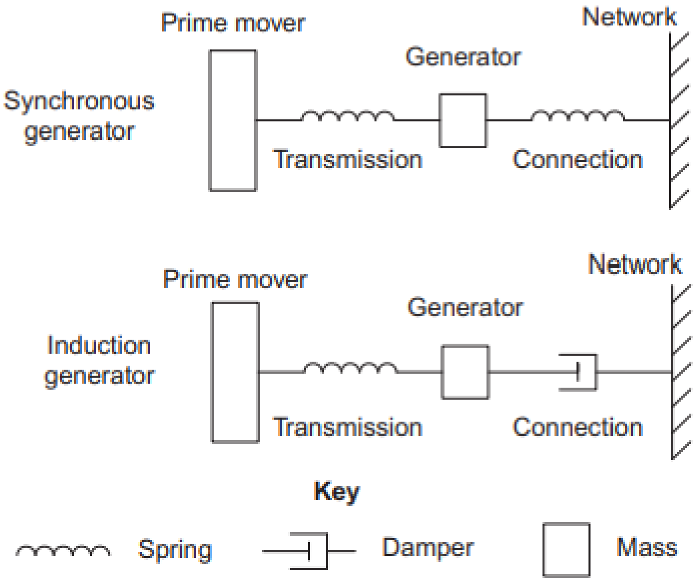


Figure ٣,٥ Simple mechanical analogues of generators

In order to improve the power factor, it is common to fit local power factor correction (PFC) capacitors at the terminals of the generator (Figure ٣,٦).
These have the effect of shifting the circle diagram, as seen by the network, downwards along the y-axis.
It is conventional to compensate for all or part of the no-load reactive power demand although, as real power is exported, there is additional reactive power drawn from the network.

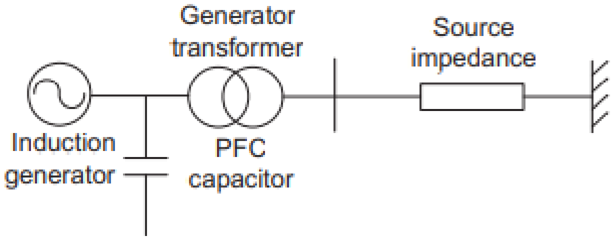


Figure ٣,٦ Induction generator connected to the infinite bus

An isolated induction generator cannot produce a terminal voltage, as there is no source of reactive power to develop the magnetic field.
Hence, when an induction generator is connected to the network there is an initial magnetizing inrush transient, similar to that when a transformer is energized, followed by a transfer of real (and reactive) power to bring the generator to its operating speed.
For a large distributed induction generator the voltage transient caused by direct-online starting is likely to be unacceptable.
Therefore, in order to control both the magnetizing inrush and subsequent transient power flows to accelerate or decelerate the generator and prime mover it is common to use a ‘soft-start’ circuit (Figure ٣,٧).
This merely consists of a back-to-back pair of thyristors that are placed in each phase of the generator connection.

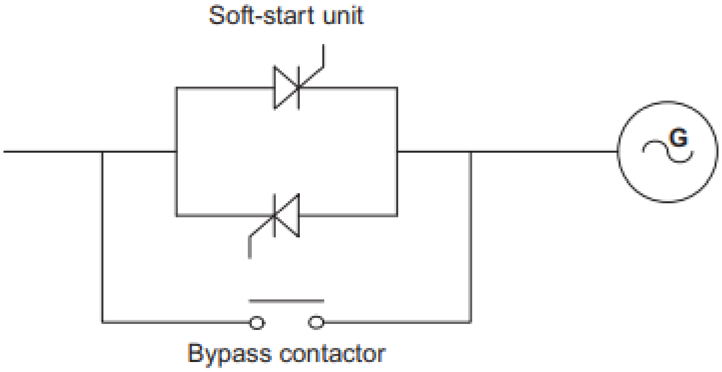


Figure ٣,٧ Soft-start unit for an induction generator (one phase only shown)

The soft start is operated by controlling the firing angle of the thyristors so building up the flux in the generator slowly and then also limiting the current that is required to accelerate the drive train.

Once the full voltage has been applied, usually over a period of some seconds, the bypass contactor is closed to eliminate any losses in the thyristors.

These soft-start units can be used to connect either stationary or rotating induction generators, and with good control circuits, can limit the magnitudes of the connection currents to only slightly more than full-load current. Similar units are, of course, widely used for starting large induction motors.

If a large induction generator, or a number of smaller induction generators, is connected to a network with a low short-circuit level then the source impedance, including the effect of any generator transformers, can become significant.

Hence, the equivalent circuit can be extended, as shown in Figure ٣,٨ to include the source impedance in the stator circuit.

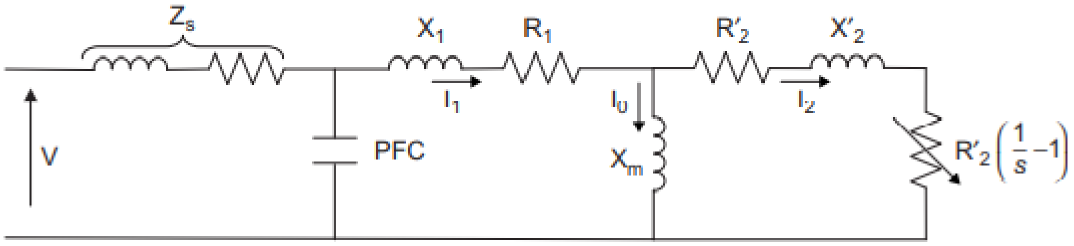
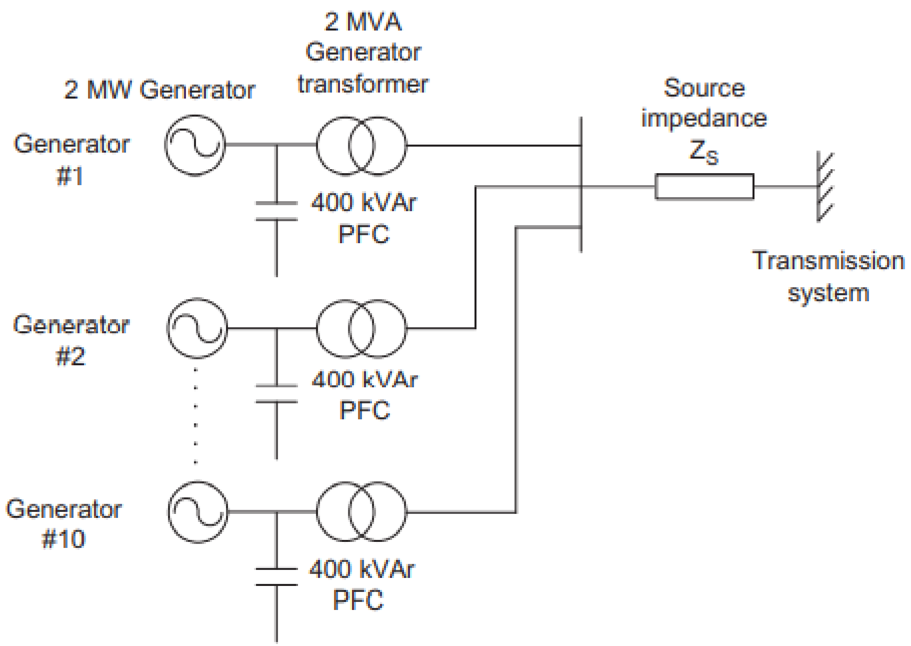


Figure ٣,٨ Steady-state equivalent circuit of induction machine connected through a source impedance (power factor correction (PFC) included)

As an example a group of ten of the ٢ MW generators, as might be found in a wind farm, is considered. Each generator is compensated with ٤٠٠ kVAr of power factor correction capacitors and connected through a ٢ MVA generator transformer of ٦٪ reactance to a busbar of short-circuit level of ٢٠٠ MVA, which is represented by the source impedance connected to an infinite busbar.

The group of ten generators is then considered as an equivalent single ٢٠ MW generator (Figure ٣,٩).

In the per unit system, this transformation is achieved conveniently by maintaining all the per-unit impedances of the generators, capacitors and transformers constant



10 × 2 MW generators, equivalent circuit

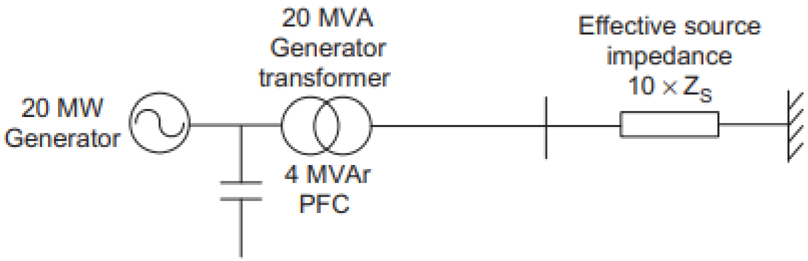


*Figure ٣,٩ Representation of ١٠ * ٢ MW coherent generators as a single ٢٠ MW generator*

merely changing the base MVA of the calculation.

This has the effect of increasing the effective impedance of the connection to the infinite busbar by the number of generators (i.e. ten).

٣.٤ Doubly fed induction generator:

A wound rotor induction machine can be operated as a variable-speed generator when a voltage is injected into the rotor circuit by an external means.

A commonly used approach is the doubly fed induction generator system (see Figure ٣,١٠), where the rotor converter controls the voltage of the wound rotor induction machine and hence its speed.

The network side converter of the rotor circuit exchanges real power with the network and maintains the DC voltage across the capacitor.

DFIG systems are now becoming widespread on large wind turbines.

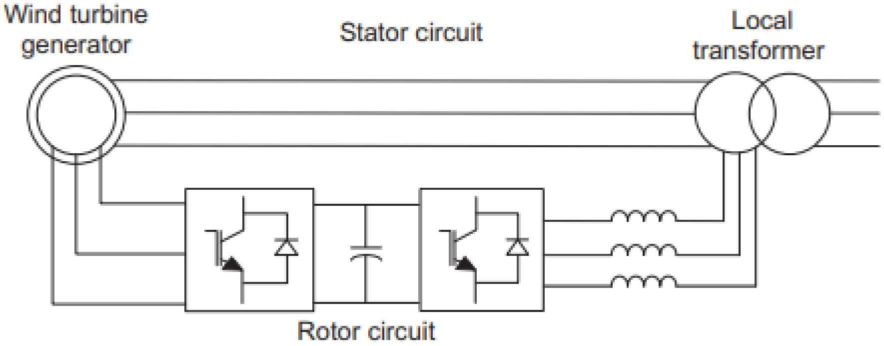


Figure ٣,١٠ Doubly fed variable-speed power electronic converter (DFIG)

In wind turbine applications, the speed of the DFIG is controlled to extract maximum power from the wind.

The power that can be extracted from the wind depends on the area swept by the turbine blades (A) and the wind speed (U) and is given by P =(١/٢)Cp ρAU^٣ , where ρ is the air density and Cp is the power coefficient [١٧].

The power coefficient depends on the tip speed ratio (λ) that is the ratio between the velocity of the rotor tip and wind speed.

Therefore for a given wind speed, in order to extract maximum power the rotor speed of the generator should be varied.

To control the generator speed, the controller shown in Figure ٣,١١ is used.
The generator control is based on a dq coordinate system,
where the q component of the stator voltage is selected as the real part of the busbar voltage and d component is the imaginary part .
This coordinate system allows the speed control action to be performed by manipulating the q component of the rotor injected voltage, Vqr.
The d component is controlled for the power factor and/or voltage control.

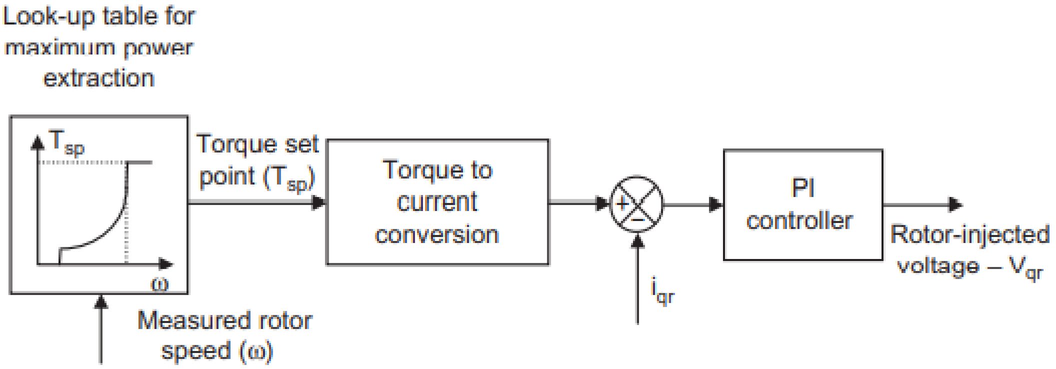


Figure ٣,١١ Torque controller for maximum power extraction

For a given injected voltage Vr = Vdr + jVqr, the performance of the DFIG wind turbine in steady state was obtained using the equivalent circuit shown in Figure ٣,١٢.

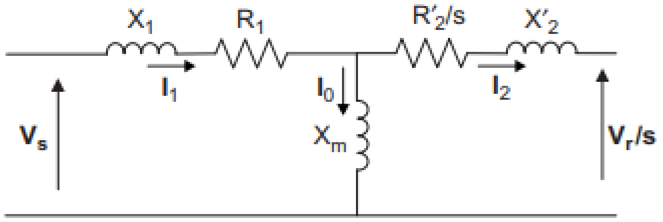


Figure ٣,١٢ Steady-state equivalent circuit of the DFIG

Figure ٣,١٣ shows the torque-slip curve of a ٢ MW generator with three different rotor-injected voltages.

The torque-slip characteristic for maximum power extraction is also shown in the figure.
When the wind speed is high (hence the torque demanded by the speed control system shown in Figure ٣,١١ is high),
the machine operates in super-synchronous speeds (point A of Figure ٣,١٣).
For lower wind speeds the machine operates in sub-synchronous speeds (point B of Figure ٣,١٣).

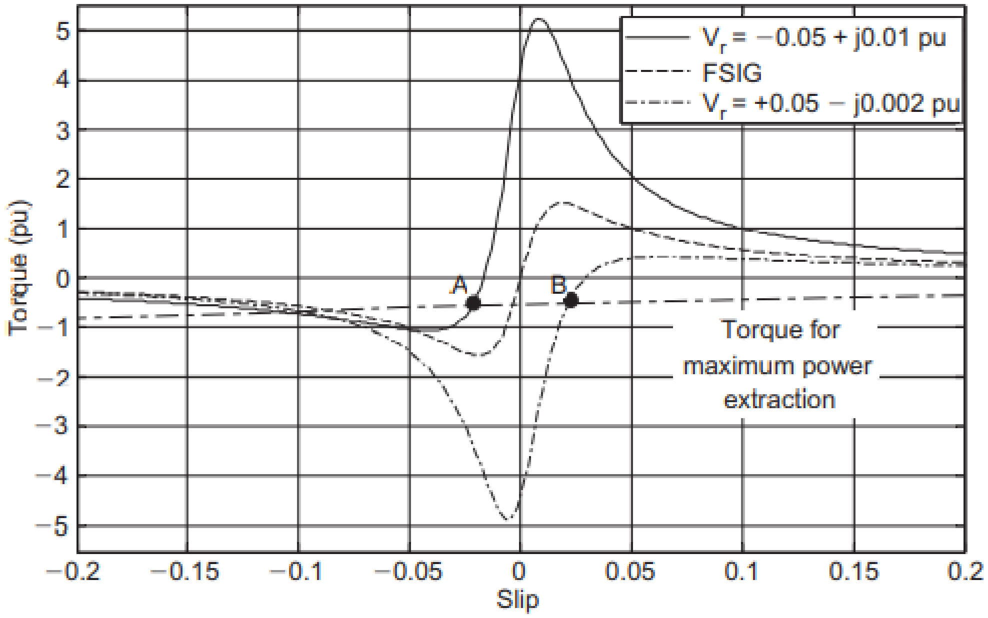


Figure ٣,١٣ Torque–slip curve for different rotor injections when a ٢ MW DFIG is connected to a ٢٠٠ MVA busbar

In a large wind farm, each DFIG wind turbine will be subjected to different wind speeds and the rotor-injected voltages that will be determined by the maximum power extraction controller are different.
The torque–speed characteristic looks very different from machine to machine.
Therefore, the analysis of a network with a DFIG wind farm may require detailed modelling of a number of generators.

In contrast, for fixed speed induction generator based wind turbines the rotor
injected voltages are zero, as the rotors are all short circuited. Thus the torque–speed characteristics of all the machines are approximately the same.
This allows the representation of a number of generators by a single coherent machine.
The DFIG wind turbine can be represented by a voltage behind a reactance in a similar manner to a synchronous generator.
The phasor diagram of the DFIG (lagging operation, exporting VArs) is shown in Figure ٣,١٤ [18].
In that diagram Eg is the voltage behind the reactance; Is, Vs and Vr are as defined in Figure ٣,١٢ and X is given by:
X = X١+(XmX٢')/(Xm+X٢')

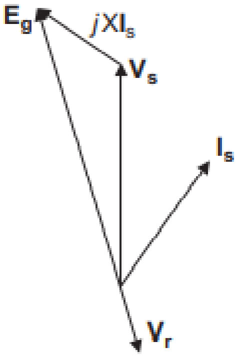


Figure ٣,١٤ Phasor diagram of the DFIG

The phasor diagram for the stator is very similar to a synchronous generator, and the capability curve for the stator can be obtained in the same way as for a synchronous generator .
The main difference comes from the rotor injection.
The total active power generation of a DFIG wind turbine is the addition of power through the stator (Ps) and power through the rotor (Pr).
The following equations were derived using the generator torque,

T and ignoring losses:

$$
\begin{aligned}
P_m &= P_s + P_r \\
T\omega_r &= T\omega_s + P_r \qquad\qquad (3.2) \\
P_r &= T(\omega_r - \omega_s) = -sT\omega_s = -sP_s
\end{aligned}
$$

where ωr is the rotor speed and ωs is the synchronous speed.

From (٣,٢), it is clear that the rotor generates power during super-synchronous operation (where slip is negative) and it absorbs power during sub-synchronous operation.

Therefore, the active power generation capability of a DFIG depends on the capability of power electronic converters and capability of stator conductors (heating limit).

The reactive power output of the DFIG is also controlled by the rotor-injected voltage. Figure ٣,١٥ shows the reactive power as a function of active power for different rotor-injected voltages obtained using the DFIG equivalent circuit (Figure ٣,١٢).

The large number of possible operating points shown in the figure were taken by changing the rotor-injected voltage from -٠,٠٥+ j٠.٠٥ to ٠,٠٥+ j٠.١٥ and limiting the stator apparent power to ١,٠ pu and the rotor apparent power to ٠,٣ pu.

The reactive power generation and absorption capability of the DFIG reduces with the active power.

In wind generation applications this often requires the wind farm operator to connect a reactive power compensation device (e.g. a STATCOM) at the point of connection as otherwise it is not possible to fulfil the Grid Code requirements for reactive power.

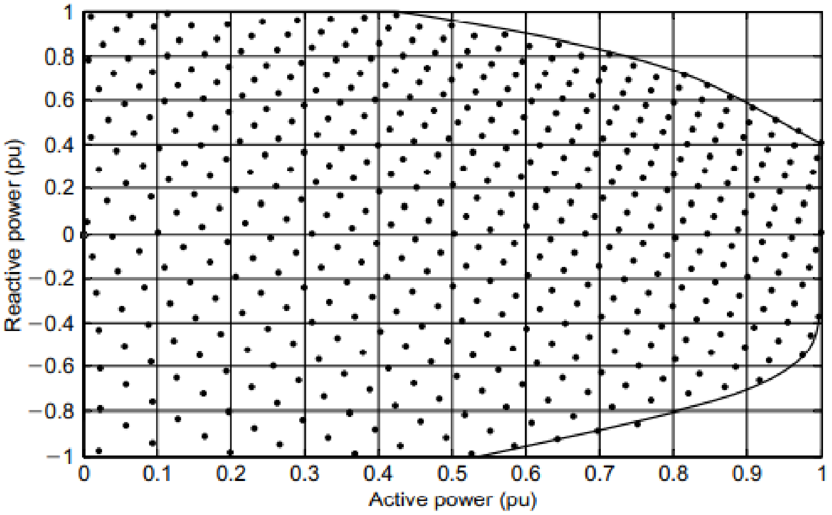


Figure ٣,١٥ Capability chart of the DFIG

٣.٥ Full power converter (FPC):

Connected generators Many renewable energy distributed generators use full power electronic converters to interface them to the network.

The purpose of the power electronic interface depends on the application.

For example in a PV system, the converter is used to convert DC generated by the PV modules to AC.

In variable-speed wind turbines, back-to-back converters are used to extract maximum power from wind.

Figure ٣,١٦ shows a converter system typically used to control a large full power converter variable-speed wind turbine.

The generator may be synchronous (wound rotor or permanent magnet) or an induction machine.

Operation is possible over a wide speed range as all the power is rectified to DC and flows through the converters.

Therefore, with typical losses of ٢–٣٪ in each converter it may be seen that, at full load, some ٤–٥٪ of the output power of the generator may be lost.

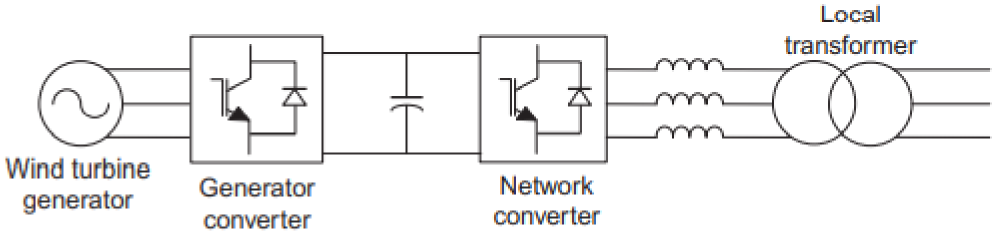


Figure ٣,١٦ Full power converter (FPC) variable-speed generator

For large (>٤٠٠ MW) offshore wind farms a long way offshore (>١٠٠ km), it may be cost effective to use HVDC (high voltage DC) HVDC can use one of the two technologies, current source converter (CSC) and voltage source converter (VSC), as shown in Figure ٣.١٧.

The CSC-based HVDC schemes are preferred for applications where power flow is very large (up to ٣٠٠٠ MW) and where there are synchronous generators to provide a commutating voltage at each end of the DC link.

For distributed generation and for DC interfaces of moderate power wind farms, VSCs are becoming the preferred choice.

For assessing their impact on the power system, VSCs can be represented by a voltage behind a reactor as shown in Figure ٣.١٨.

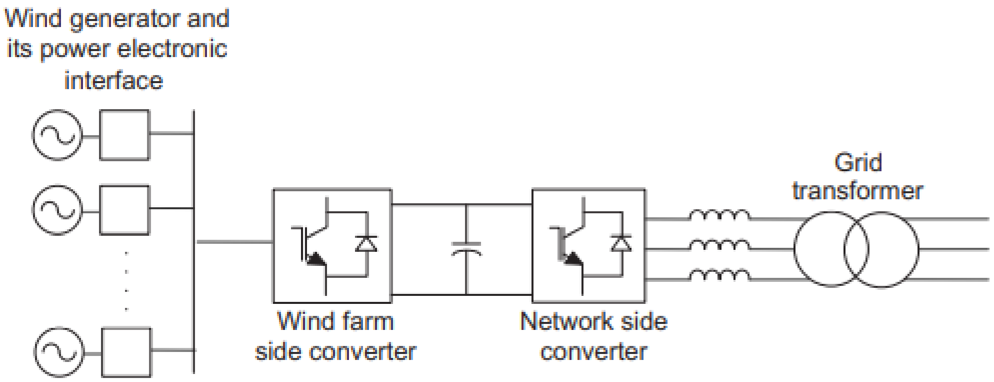
This representation can be used for VSC HVDC as well as full power converter wind turbines and even some photovoltaic systems.

Generally a phase locked loop (PLL) is employed to obtain the grid or generator side voltage (busbar B) phase angle and frequency.

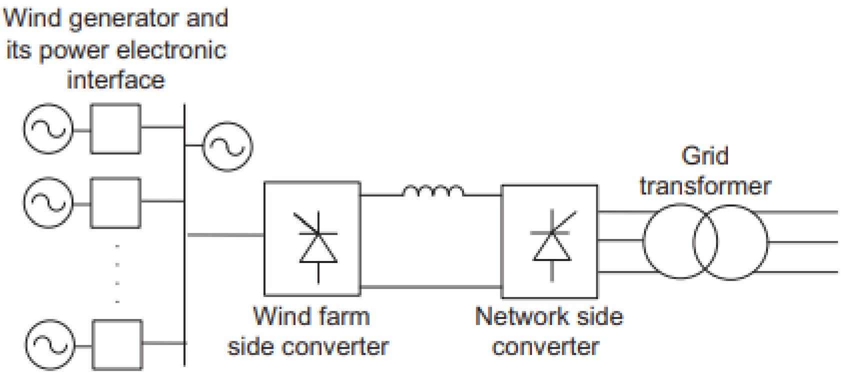
A controller then turns ON and OFF the switches in the VSC to generate a voltage at busbar A with a phase angle relative to busbar B (depending on the control strategy).

For system studies, neglecting higher-order harmonics generated by the VSC, this is represented by two voltage sources with reactive coupling between them.

With a VSC, sinusoidal current can only be injected if the IGBTs are switched rapidly.
This leads to electrical losses, which may not be as commercially significant in a large motor drive as they will be in a distributed generation scheme.
Thus, for large generators alternative arrangements may be considered including the use of multi-level inverters to combine a number of voltage sources or by combining multiple inverters together through transformers of differing vector groups to form multiphase inverters.
The technique chosen will depend on an economic appraisal of the capital cost and the cost of losses, and as technology in this area is developing rapidly



Voltage source converter based HVDC connection



Current source converter based HVDC connection

Figure ٣. ١٧ Power electronic converter interfaces for large wind farms

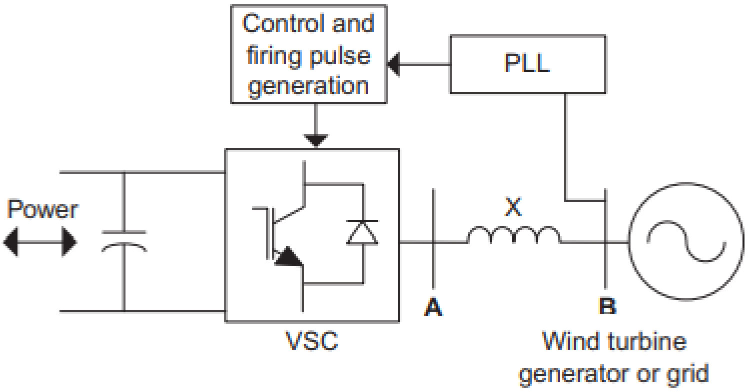


Figure ٣, ١٨ AC side connection of a VSC

so the most cost-effective technique at any rating will change over time. Future developments of power electronic converters for distributed generation plant may involve the use of soft-switching converters to reduce losses, resonant converters are already used in small photovoltaic generators, and include other converter topologies that eliminate the requirement for the explicit DC link.

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