Chapter 2
Literature Review and Power Quality Issues

2.1 Literature Survey

The main feature of the radial distribution network (RDN) is those power losses due to its high R/X ratio which leads to about 10–13% losses of the generated power [7]. Thus, two solutions can be applied is inclusion of distributed generators and/or compensators. Distributed generators (DGs) have recently been incorporated in RDN for electrical quality, economic anxiety, and environmental concerns. Distributed generators can be defined as electric power resources with limited capacity connected to electric systems closed to users. There are many types of DGs based on their technology including microturbines, fuel cells, combustion engines, wind turbines, geothermal, photovoltaic, and hydro systems [8, 9]. Photovoltaic-based distributed generation (PV-DG) is one of the new renewable energy resources that is widely incorporated in distribution networks for numerous benefits for providing environmental, technical, and economic benefits [10, 11].

Integration of renewable distributed generators and the shunt compensators is an effective solution from technical and economic perspectives. Several renewable-based technologies have been progressed to generate the required electricity, including wind turbine, biomass, solar thermal, solar PV, geothermal, and hydro systems [12]. Distribution flexible AC transmission systems (D-FACTS) are also widely embedded in the distribution grid [13]. D-FACTS include numerous controllers such as distribution static VAR compensator (D-SVC), unified power quality conditioner (UPQC), and distributed static compensator (D-STATCOM). The inclusion of DGs can yield several economic, technical, and environmental benefits. It can also reduce the power loss, reduce the voltage deviation, maximize the system reliability, decrease the emissions of greenhouse gases, and diminish the generation cost [10].

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The optimal integration of D-STATCOM in distribution grids had been presented in [14]; the immune algorithm had been employed to assign the siting and sizing of the D-STATCOM for cost and loss reduction. Harmony Search Algorithm had been implemented to optimize the site and size of the D-STATCOM for loss reduction. In [6], the bat algorithm was applied for optimizing the site and size of the D-STATCOM for losses reduction with multi-load levels. The binary gravitational search technique had been employed to assign the site and size of the D-STATCOM for enhancement [15]. They applied the imperialist competitive algorithm to determine the optimal location and size of the D-STATCOM for a multi-objective function under uncertainties of the load demand. A Bio-Inspired Cuckoo Search technique has been used for optimizing the allocation of the D-STATCOM for loss reduction under different load models. The differential evolution algorithm has been used to assign the location and size of D-STATCOM for cost and loss reduction [16–18]. The site and size of the D-STATCOM were allocated to reduce the losses and boost the stability and the voltage profile using a multi-objective sine cosine algorithm. The fuzzy-GA-based algorithm has been employed to optimize the allocation of the D-STATCOM for reducing losses and the total cost [19]. Numerous efforts have been presented to allocate the PV-DG in the power system. The particle swarm optimization (PSO) had been employed to allocate the D-STATCOM and DG for reducing the losses and supporting the voltage [20].

Incorporating renewable distributed energy resources (RDERs) in distribution networks such as solar PV units are challenging due to seasonal and daily variations of the solar irradiance and the weather variations that increase the uncertainty in the power system. Thus, it is mandatory to consider the uncertainties of the RDERs for efficient planning in the power system. Several efforts have been presented to integrate the DGs under the uncertainties. In [21], the optimal planning problem has been solved with RDERs considering uncertainties of solar radiation, load demand, and wind speed. The [22] assigned of DGs' optimal size and site under uncertainties of the RDER fuel price and future load growth. In Refs. [23, 24], the optimal reactive power dispatch problem has been solved under the uncertainties of renewable sources. In Refs. [25, 26], the optimal site and a rating of the RDERs have been assigned optimally under uncertainties of the solar radiation, wind speed, and load demand.

PV units convert the solar irradiance to DC power by its solar cells, and then an inverter is utilized to invert the DC voltage to an AC voltage. There are two options for connecting the PV system: the first installation is that the PV is connected to the electric grid which is known as an on-grid PV system connected, and the other connection is organized by feeding a stand-alone system known as an off-grid PV system. Several optimizations have been used for assigning the optimal capacity of PV units such as genetic algorithm, artificial bee colony [27], grasshopper optimization algorithm, moth flame optimizer, lightning attachment procedure optimization, backtracking search optimization [28], and ant lion optimization [29].

The reactive power compensation is an excellent solution for minimizing the system loss and enhancing the performance of the RDN. Reactive power compensation can be achieved by the installation of distributed flexible AC transmission system (D-FACTS) devices such as unified power quality conditioner (UPQC), distribution static VAR compensator (D-SVC), and D-STATCOM [15]. D-STATCOM is an effective controller where it is installed in a shunt to control the voltage magnitude of a certain bus by injecting or absorbing reactive power to the system through its voltage source convert connected to the system through coupling transformer [30]. D-STATCOM is installed for important technical and economic reasons related to the RDN such as power quality, loss minimization, harmonic mitigation, voltage stability, and voltage profile improvement [31].

Several excellent efforts have been done to assign the optimal placement and rating of the DSTATCM such as Taher and Afsari optimal location and setting of D-STATCOM in distribution networks used immune algorithm (IA) for reducing power congestion, energy loss, cost, and the voltage profile improvement [14], Devi and Geethanjali [32] applied particle swarm optimization (PSO) to assign the rating and location of the D-STATCOM and the distributed generation (DG) to alleviate the power loss and improvement the voltage profile. Ref. [6] applied the differential evolution algorithm (DE) to reduce the losses by the optimal reconfiguration and D-STATCOM. A binary gravitational search algorithm (BGSA) has been employed to solve the allocation problem of the D-STATCOM for reliability enhancement [15]. Cat swarm optimization has been used to assign the size and rating of the D-STATCOM to alleviate the power loss and improvement the voltage profile [33]. In Ref. [34], the optimal allocation of DG and D-STATCOM using a cuckoo searching algorithm was applied. In Ref. [35] a Particle Swarm Optimization algorithm for finding the optimal location and sizing of Distributed Generation and Distribution Static Compensator (D-STATCOM) with the aim of reducing the total power loss along with voltage profile improvement of Radial Distribution System is proposed. In Ref. [36], bacterial foraging optimization algorithm has been used to solve the allocation problem of DG and D-STATCOM for minimization of the loss and voltage deviation.

2.2 Distributed Generation Background

2.2.1 Definition of 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 [37]. When connected to the electric utility's lower-voltage distribution lines, distributed generation can help support the delivery of clean, reliable power to additional customers and reduce electricity losses along transmission and distribution lines [38, 39]. The concept of DG contrasts with the traditional centralized power generation concept, where the electricity is generated in large power stations and is transmitted to the end-users through transmission and distributions

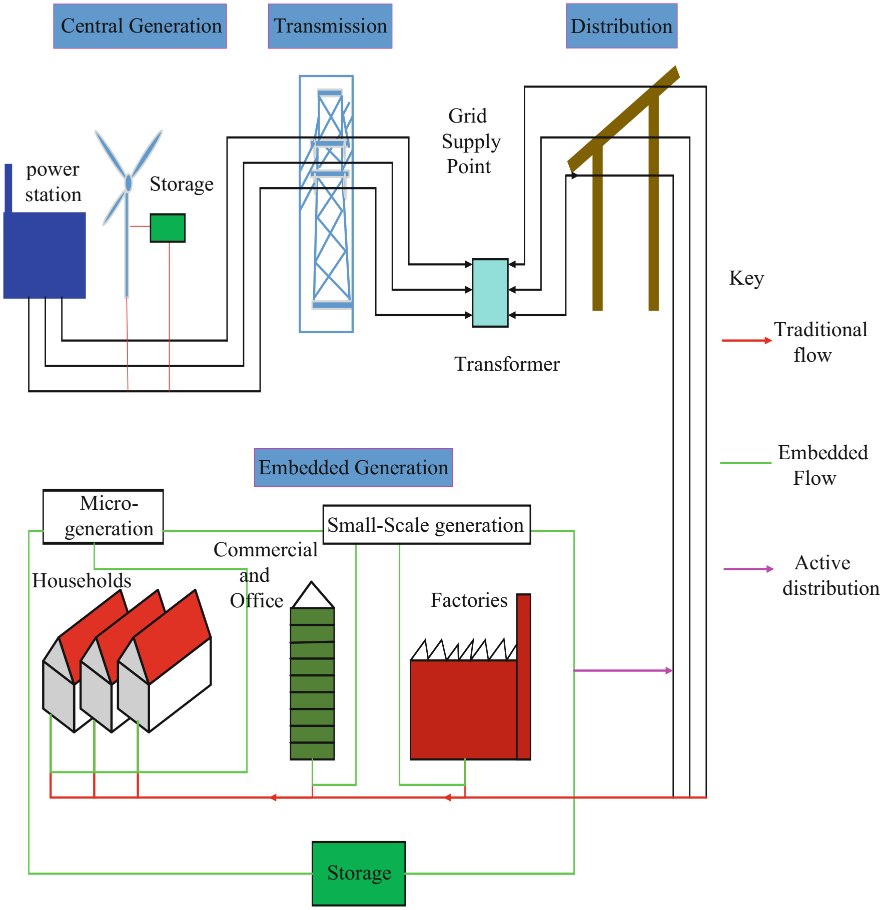


Fig. 2.1 Distributed electricity systems

lines in Fig. 2.1. While central power systems remain critical to the global energy supply, their flexibility to adjust to changing energy needs is limited. Central power is composed of large capital-intensive plants and a transmission and distribution (T&D) grid to disperse electricity [40].

A distributed electricity system is one in which small and microgenerators are connected directly to factories, offices, and households and to lower voltage distribution networks. Electricity not demanded by the directly connected customers is fed into the active distribution network to meet demand elsewhere. Electricity storage systems may be utilized to store any excess generation. Large power stations and large-scale renewables, e.g. [41], offshore wind, remain connected to the high-voltage transmission network providing national backup and ensuring the quality of supply [38]. Again, storage may be utilized to accommodate the variable output of some forms of generation. Such a distributed electricity system is represented in Fig. 2.1 below.

In the residential sector, common distributed generation systems include:

- Solar photovoltaic panels
- Small wind turbines
- Natural-gas-fired fuel cells
- Emergency backup generators, usually fuelled 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, may be fuelled by oil [42].

2.3 The Cost Structure of Distributed Generation Technologies

The direct costs of distributed generation to customers include the installed cost of the equipment, fuel costs, nonfuel operation, and maintenance (O&M) expenses, and certain costs that the customers' utility imposes [43]. To make this comparison of costs most useful, the following cost data assume that for each technology, there are used an installed capacity, a rate of utilization, and (in some cases) a geographic location that would be suitable for serving the electricity needs of individual customers. For example, the costs for the wind turbine discussed here are for a size that might be used in a small rural business (such as a farm) in a location with favorable wind resources [44].

On that basis, data compiled from various industry and government sources describe the current costs of the most common types of electricity generation technologies. Data for a combined-cycle unit are presented as well; as the largest source of additional electricity from utilities and independent power producers, combined-cycle systems provide a representative benchmark against which the costs of other technologies can be measured [43].

2.4 Capital Costs

The costs of acquiring and installing generating units vary widely, depending on technology, capacity, and other factors. The US Department of Energy estimates that the typical installed capital costs for distributed generators range from under $1000 per kilowatt for a combustion turbine to almost $7000 per kilowatt for a solar photovoltaic system. Among small-capacity technologies, internal combustion engines (fuelled by diesel and gasoline) have the lowest capital costs and highest operating costs. Renewable technologies (using wind and solar power) have the highest capital costs and lowest operating costs [44].

2.5 Distributed Generation Applications and Technology

2.5.1 Distributed Generation Applications

Distributed generation (DG) is currently being used by some customers to provide some or all their electricity needs. There are many different potential applications for DG technologies. For example, some customers use DG to reduce demand charges imposed by their electric utility, while others use it to provide primary power or reduce environmental emissions. DG can also be used by electric utilities to enhance their distribution systems. Many other applications for DG solutions exist. The following is a list of those of potential interest to electric utilities and their customers [43, 45].

2.5.1.1 Continuous Power

In this application, the DG technology is operated at least 6000 hours a year to allow a facility to generate some or all its power on a relatively continuous basis. Important DG characteristics for continuous power include:

- High electric efficiency
- Low variable maintenance costs
- Low emissions

Currently, DG is being utilized most often in a continuous power capacity for industrial applications such as food manufacturing, plastics, rubber, metals, and chemical production. Commercial sector usage, while a fraction of total industrial usage, includes sectors such as grocery stores and hospitals [39].

2.5.1.2 Combined Heat and Power (CHP)

Also referred to as cooling, heating, and power or cogeneration, this DG technology is operated at least 6000 hours per year to allow a facility to generate some or all its power. A portion of the DG waste heat is used for water heating, space heating, steam generation, or other thermal needs. In some instances, this thermal energy can also be used to operate special cooling equipment. Important DG characteristics for combined heat and power include [46]:

- High useable thermal output (leading to high overall efficiency)
- Low variable maintenance costs
- Low emissions

CHP characteristics are like those of continuous power, and thus the two applications have almost identical customer profiles, though the high thermal demand here is not necessary for continuous power applications. As with continuous power, CHP is most used by industry clients, with a small portion of overall installations in the commercial sector [39].

2.5.1.3 Peaking Power

In a peaking power application, DG is operated between (200–3000) hours per year to reduce overall electricity costs. Units can be operated to reduce the utility demand charges, to defer buying electricity during high-price periods, or to allow for lower rates from power providers by smoothing site demand. Important DG characteristics for peaking power include [46]:

- Low installed cost
- Quick start-up
- Low fixed maintenance costs

Peaking power applications can be offered by energy companies to clients who want to reduce the cost of buying electricity during high-price periods. Currently, DG peaking units are being used mostly in the commercial sector, as load profiles in the industrial sector are relatively flat. The most common applications are in educational facilities, lodging, miscellaneous retail sites, and some industrial facilities with peaky load profiles [39].

2.5.1.4 Green Power

DG units can be operated by a facility to reduce environmental emissions from generating its power supply. Important DG characteristics for green power applications include:

- Low emissions
- High efficiency
- Low variable maintenance costs

Green power could also be used by energy companies to supply customers who want to purchase power generated with low emissions [39, 47].

2.5.1.5 Premium Power

DG is used to provide electricity service at a higher level of reliability and/or power quality than typically available from the grid. The growing premium power market presents utilities with an opportunity to provide a value-added service to their clients. Customers typically demand uninterrupted power for a variety of applications, and for this reason, premium power is broken down into three further categories [48].

2.5.1.6 Emergency Power System

This is an independent system that automatically provides electricity within a specified time frame to replace the normal source if it fails. The system is used to power critical devices whose failure would result in property damage and/or threatened health and safety. Customers include apartment, office and commercial buildings, hotels, schools, and a wide range of public gathering places [39].

2.5.1.7 Standby Power System

This independent system provides electricity to replace the normal source if it fails and thus allows the customer entire facility to continue to operate satisfactorily. Such a system is critical for clients like airports, fire and police stations, military bases, prisons, water supply and sewage treatment plants, natural gas transmission and distribution systems, and dairy farms [49].

2.5.1.8 True Premium Power System

Clients who demand uninterrupted power, free of all power quality problems such as frequency variations, voltage transients, dips, and surges, use this system. Power of this quality is not available directly from the grid – it requires both auxiliary power conditioning equipment and either emergency or standby power. Alternatively, a DG technology can be used as the primary power source, and the grid can be used as a backup [50]. This technology is used by mission critical systems like airlines, banks, insurance companies, communications stations, hospitals, and nursing homes.

Important DG characteristics for premium power (emergency and standby) include:

- Quick start-up
- Low installed cost
- Low fixed maintenance costs

2.5.1.9 Transmission and Distribution Deferral

In some cases, placing DG units in strategic locations can help delay the purchase of new transmission or distribution systems and equipment such as distribution lines and substations. A detailed analysis of the life-cycle costs of the various alternatives is critical, and issues relating to equipment deferrals must also be examined closely. Important DG characteristics for transmission and distribution deferral (when used as a "peak deferral") include [39]:

- Low installed cost
- Low fixed maintenance costs

2.5.1.10 Ancillary Service Power

DG is used by an electric utility to provide ancillary services (interconnected operations necessary to affect the transfer of electricity between the purchaser and the seller) at the transmission or distribution level. In markets where the electric industry has been deregulated and ancillary services unbundled (in the United Kingdom, for example), DG applications offer advantages over currently employed technologies [39].

Ancillary services include spinning reserves (unloaded generation, which is synchronized and ready to serve additional demand) and non-spinning, or supplemental, reserves (operating reserve is not connected to the system but can serve demand within a specific time or interruptible demand that can be removed from the system within a specified time). Other potential services range from transmission market reactive supply and voltage control, which uses generating facilities to maintain a proper transmission line voltage, to distribution level local area security, which provides back up power to end-users in the case of a system fault [48].

The characteristics that may influence the adoption of DG technologies for ancillary service applications will vary according to the service performed and the ultimate shape of the ancillary service market [51, 52]. Figure 2.2 summarizes the different kinds of DG applications.

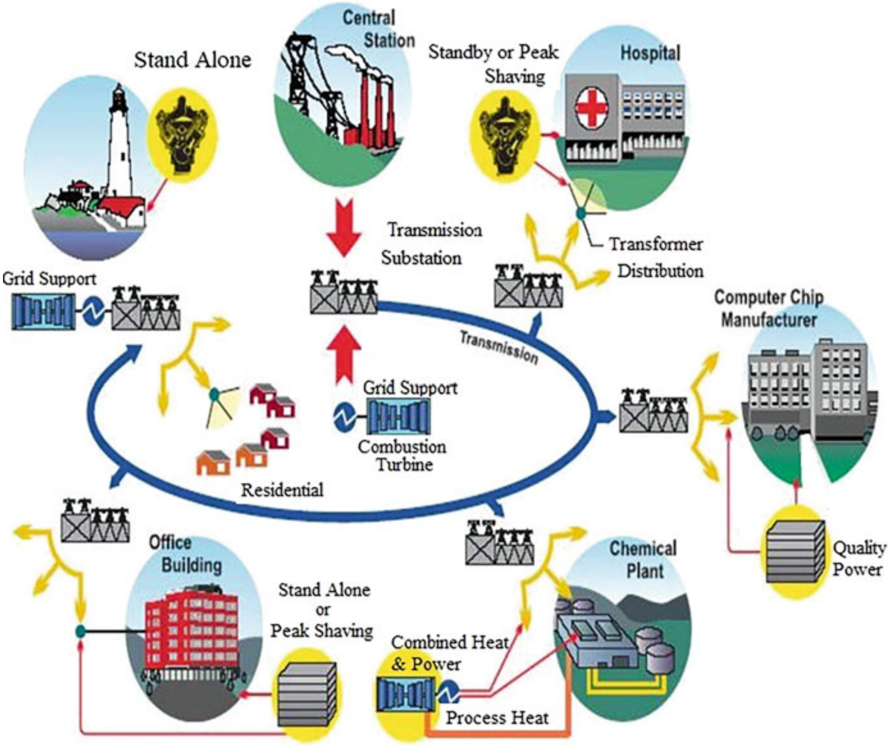


Fig. 2.2 Summary of DG applications [39]

2.5.2 *Distributed Generation Technologies*

2.5.2.1 Reciprocating Engines

The distributed generation technology was developed more than a century ago and is still widely utilized in a broad array of applications. The engines range in size from less than 5 to over 5000 kW and use diesel, natural gas, or waste gas as their fuel source. Development efforts remain focused on improving efficiency and reducing emission levels. Reciprocating engines are being used primarily for backup power, peaking power, and in cogeneration applications [48].

2.5.2.2 Microturbines

A new and emerging technology, microturbines are currently only available from a few manufacturers. Other manufacturers are looking to enter this emerging market, with models ranging from 30 to 200 kW. Microturbines promise low emission levels, but the units are currently relatively expensive. Obtaining reasonable costs and demonstrating reliability will be major hurdles for manufacturers. Microturbines are just entering the marketplace, and most installations are for the purpose of testing the technology [39].

2.5.2.3 Industrial Combustion Turbines

A mature technology, combustion turbines range from 1 MW to over 5 MW. They have low capital cost, low emission levels, but also usually low electric efficiency ratings. Development efforts are focused on increasing efficiency levels for this widely available technology. Industrial combustion turbines were being used primarily for peaking power and in cogeneration applications [39].

2.5.2.4 Photovoltaic

Commonly known as solar panels, (PV) panels are widely available for both commercial and domestic use. Panels range from less than 5 kW, and units can be combined to form a system of any size. They produce no emissions and require minimal maintenance. However, they can be quite costly. Less expensive components and advancements in the manufacturing process are required to eliminate the economic barriers now impeding wide-spread use of PV systems. PV is currently being used primarily in remote locations without grid connections and to generate green power [49].

2.5.2.5 Fuel Cells

Fuel cells not only are very efficient but also have very low emission levels. A fuel cell operates like a battery. It supplies electricity by combining hydrogen and oxygen electrochemically without combustion. However, while the battery is a storage device for energy that is eventually used up and/or must be recharged, the fuel cell is permanently fed with fuel and an oxidant, so that the electrical power generation continues. The final product is pure water; the electrochemical reaction generates electricity and heat without a flame (“cold combustion”). A single cell provides less than one volt, so a series of fuel cells are normally “stacked” one on another to increase the power output. The basic fuel cell has two electrodes separated by an electrolyte [39].

One of the electrodes (the anode) is supplied with the fuel (for example, hydrogen or natural gas). The second electrode (the cathode) is supplied with oxygen by simply pumping air in. The few fuel cells currently being used provide premium power. There are several types of fuel cells. Proton exchange membrane fuel cells are now days the most commercially available type. They have the highest energy density per volume rate, and their prices are expected to fall fast because they are being adapted by the automotive industry for transportation use [53].

2.5.2.6 Wind Turbine Systems

Wind turbines are currently available from many manufacturers and range in size from less than 5 to over 1000 kW. They provide a relatively inexpensive (compared to other renewables) way to produce electricity, but as they rely upon, the variable and somewhat unpredictable wind are unsuitable for continuous power needs. Development efforts look to pair wind turbines with battery storage systems that can provide power in those times when the turbine is not turning. Wind turbines are being used primarily in remote locations not connected to the grid and by energy companies to provide green power [39].

2.6 Power Quality Impact of PV-DG

The integration of PV-DG in power systems can alleviate overloading in transmission lines, provide peak shaving, and support the general grid requirement. However, improper coordination, location, and installation of PV-DG may affect the power quality of power systems. Most conventional power systems are designed and operated such that generating stations are far from the load canters and use the transmission and distribution system as pathways. The normal operation of a typical power system does not include generation in the distribution network or in the customer side of the system [54].

However, the integration of PV-DG in distribution systems changes the normal operation of power systems and poses several problems which include possible bidirectional power flow, voltage variation, breaker no coordination, alteration in the short circuit levels, and islanding operation [55, 56]. Therefore, studies are required to address the technical challenges caused by DG integration in distribution systems. The interconnection device between the DG and the grid must be planned and coordinated before connecting any DG.

2.7 Distributed Static Compensator (D-STATCOM)

With the growth and development of power grids, optimal utilization of electric networks is very important. Because of the high cost of construction and development of power networks, mitigation of existing issues, such as excessive power losses, voltage profile problems, voltage instabilities, reliability problems, etc., is inevitable. To obviate these problems, distribution synchronous static compensator (D-STACTOM) as a shunt compensator device can be used in electric distribution networks. The optimal location and size of D-STACOM should be determined because of economic viability, required quality, reliability, and availability [57].

In recent years, several theses have concentrated on the techniques used for finding optimal location and size of the D-STATCOM units considering different aspects. However, to date, no review chapter has been published in this field. The chapter presents an up-to-date survey of the literature on the optimal allocation of D-STATCOM in distribution networks. The existing research works have been classified into five categories including analytical methods, artificial neural network-based approaches, metaheuristic methods, sensitivity approaches, and a combination of sensitivity approaches and metaheuristic methods. Moreover, it was found that in the D-STATCOM allocation problem, the objectives may be the alleviation of power loss, mitigation of voltage deviations, improvement of reliability metrics, and enhancement of voltage stability [58].

Increased loading and the need for economic efficiency of electric power networks have prompted companies to use transmission and distribution networks at the highest possible efficiency and loading [59]. Some challenges associated with these networks include stability issues, high losses, and excessive voltage drops in buses [60 - 62]. These challenges usually occur when there is an indiscriminate increase in nonlinear loads [63]. A voltage drop in the distribution network may be caused by distribution lines with high impedance or growing loads in three-phase or unbalanced loads. Today’s advanced distribution networks take on a more sophisticated form due to the incorporation of distributed generation units that redirect the flow of current through the lines [64]. Nowadays, there is a general consensus on this idea that power electronics devices and methods are more suitable than traditional methods that were working based on electromechanical technologies and have low speed and high cost [65]. Using flexible alternating current transmission system (FACTS), devices is inevitable for optimal utilization of current electric networks [66, 67].

Power electronics-based controllers in power distribution systems help to provide energy with an appropriate quality for subscribers [68, 69]. In general, custom power (CP) devices, which are similar to FACTS devices, are a useful solution to address the problem of interruptions and poor power quality in power networks [70] . Although FACTS and CP devices share a common technical base, they have different performance goals. FACTS devices are used in the transmission, while CP devices are used in distribution. CP devices are especially effective in system reliability and power quality. Distribution static compensator (D-STATCOM) is a shunt CP device, used in distribution networks. It is used to improve power quality (i.e., power factor, voltage profile, voltage stability). The ability to inject and absorb reactive power with very fast, dynamical responses made its application very wide within the field. D-STATCOM injects current into the system at the point of common coupling, which helps in power factor correction, harmonic filtering, etc. [31]. A review of the literature indicates that potential applications of D-STATCOM include reactive power compensation, voltage support, circulating excess power among the phases, and reduction of fluctuations caused by photovoltaic systems [71].

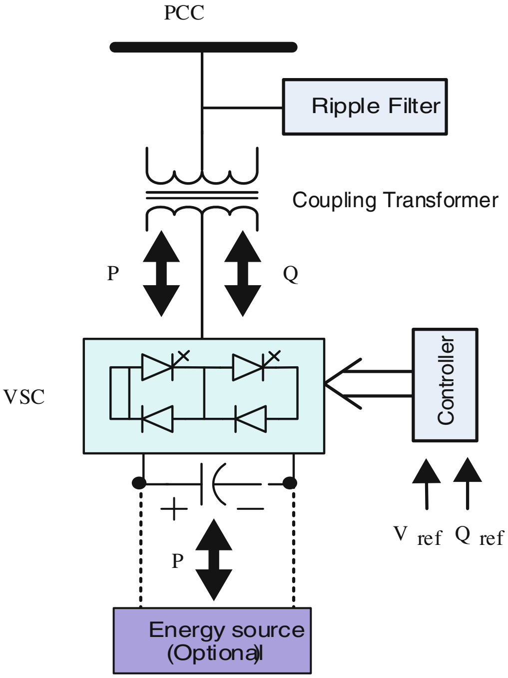


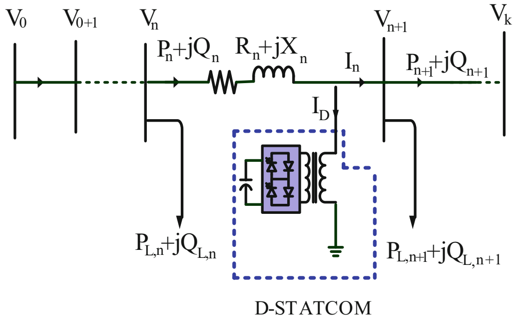
Fig. 2.3 Schematic diagram of D-STATCOM device

New members of FACTS controllers have been emerged due to continuous progress of power electronic devices. D-STATCOM is a developed controller based on voltage source converter (VSC). D-STATCOM can inject or absorb both active and reactive power at a point of common coupling connection (PCC) by injecting a variable magnitude and phase angle voltage at PCC. D-STATCOM is incorporated in electric systems for enhancing the power quality, improving the power factor, balancing the loading, mitigating the harmonic, reactive power compensation, reducing the power fluctuations of photovoltaic units minimizing the voltage sag, mitigating the flicker in the electric system, and minimizing the power losses [31, 71–74].

D-STATCOM consists of voltage source converter, DC bus capacitor, ripple filter, and coupling transformer as shown in Fig. 2.3. VSC is constructed by using insulated gate bipolar transistors (IGBT), Gate Turn-off thyristor (GTO), and MOSFET where the switching of component is based on pulse-width modulation (PWM) sequences. The coupling transformer is utilized for matching the inverter voltage with the bus voltage. The D-STATCOM topologies are categorized based on three-phase three-wire (3P3W) and three-phase four-wire (3P4W) as illustrated in [75, 76].

D-STATCOM can exchange active and reactive current with the network. A steady-state modeling D-STATCOM has presented [75]. Figure. 2.4 shows D-STATCOM controller which included in radial distribution system at bus $n + 1$ where D-STATCOM inject or absorb I_D at this bus. By applying KVL, the voltage at bus $n + 1$ can be obtained as:

Fig. 2.4 A Radial distribution system with D-STATCOM



$$V_{n+1} \angle\theta_{n+1} = V_n \angle\theta_n - (R_n + jX_n)\left(I_n \angle\delta + I_{\mathrm{D}} \angle\left(\theta_{n+1} \pm \frac{\pi}{2}\right)\right) \tag{2.1}$$

where

$V_{n+1} \angle \theta_{n+1}$ is voltage of bus n + 1 after inclusion D-STATCOM,
I_{D} is the injected current by D-STATCOM, and
I_n is the line current after inclusion of DSTACOM.

Equation (2.1) represents the essential idea for modeling D-STATCOM which can be solved by separating it to real and imaginary terms as follows:

$$\begin{aligned} V_{n+1}\mathrm{Cos}(\theta_{n+1}) &= Re(V_n \angle\theta_n) - Re(I_n \angle\delta(R_n + jX_n)) \\ &\quad + X_n I_{\mathrm{D}}\mathrm{Sin}\left(\theta_{n+1} + \frac{\pi}{2}\right) - R_n I_{\mathrm{D}}\mathrm{Cos}\left(\theta_{n+1} + \frac{\pi}{2}\right) \end{aligned} \tag{2.2}$$

where $R_n + jX_n$ is the reactance and resistance between bus ($_{n+1}$), I_{D} is the injected current by D-STATCOM, I_n is the line current after inclusion of DSTACOM, *Re* is the real part, and θ_{n+1} is the vase defiance between voltage of bus V_n, V_{n+1}

$$\begin{aligned} V_{n+1}\mathrm{Sin}(\theta_{n+1}) &= Im(V_n \angle\theta_n) - Im(I_n \angle\delta(R_n + jX_n)) \\ &\quad - X_n I_{\mathrm{D}}\mathrm{Cos}\left(\theta_{n+1} + \frac{\pi}{2}\right) - R_n I_{\mathrm{D}}\mathrm{Sin}\left(\theta_{n+1} + \frac{\pi}{2}\right) \end{aligned} \tag{2.3}$$

Equations (2.2) and (2.3) can be simplified as follows:

$$a\mathrm{Cos}x_2 = k_1 - b_1 x_1 \mathrm{Sin}x_2 - b_2 x_1 \mathrm{Cos}x_2 \tag{2.4}$$

$$a\mathrm{Sin}x_2 = k_2 - \mathrm{b}_2 x_1 \mathrm{Sin}x_2 + \mathrm{b}_1 x_1 \mathrm{Cos}x_2 \tag{2.5}$$

where

$$k_1 = Re(V_n \angle\theta_n) - Re(I_n \angle\delta(R_n + jX_n)) \tag{2.6}$$

$$k_2 = Im(V_n \angle\theta_n) - Im(I_n \angle\delta(R_n + jX_n)) \tag{2.7}$$

$$a = V_{n+1} \tag{2.8}$$

$$b_1 = -R_n$$

$$b_2 = -X_n$$

$$x_1 = I_{\mathrm{D}}$$

$$x_2 = \theta_{n+1}$$

Equations (2.4) and (2.5) can be rewritten as follows:

$$x_1 = \frac{a\mathrm{Cos}x_2 - k_1}{-b_1\mathrm{Sin}x_2 - b_2\mathrm{Cos}x_2} \tag{2.9}$$

$$x_1 = \frac{a\mathrm{Sin}x_2 - k_2}{-b_2\mathrm{Sin}x_2 + b_1\mathrm{Cos}x_2} \tag{2.10}$$

By equating Eqs. (2.9) and (2.10)

$$(k_1b_2 - k_2b_1)\mathrm{Sin}(x_2) + (-k_1b_1 - k_2b_2)\mathrm{Cos}(x_2) + ab_1 = 0 \tag{2.11}$$

The previous equation can be simplified as:

$$\left(d_1^2 + d_2^2\right)x^2 + (2d_1ab_1)x + \left(a^2b_1^2 - d_2^2\right) = 0 \tag{2.12}$$

where it is assumed that:

$$x = \mathrm{Sin}(x_2)$$

$$d_1 = (k_1b_2 - k_2b_1)$$

$$d_2 = (-k_1b_1 - k_2b_2)$$

Hence, Eq. (2.12) can be solved as follows:

$$x = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{2.13}$$

where

$$A = \left(d_1^2 + d_2^2\right)$$

$$B = (2d_1ab_1)$$

$$C = \left(a^2 b_1^2 - d_2^2\right)$$

Hence,

$$\theta_{n+1} = \mathrm{Sin}^{-1}(x) \tag{2.14}$$

The value of I_D can be obtained simply from (2.6) or (2.7). The voltage at PCC, the D-STATCOM current, and injected reactive power by D-STATCOM can be found as follows:

$$\overrightarrow{V_{n+1}} = V_{n+1} \llcorner \theta_{n+1} \tag{2.15}$$

$$\overrightarrow{I_\mathrm{DStatcom}} = I_\mathrm{DStatcom} \llcorner \left(\theta_{k+1} + \frac{\pi}{2}\right)\overrightarrow{I_\mathrm{DStatcom}} \tag{2.16}$$

$$Q_\mathrm{D} = Im\left(V_{n+1} \llcorner \theta_{n+1}\left(\mathrm{I}_D \llcorner \left(\theta_{n+1} + \frac{\pi}{2}\right)\right)^*\right) \tag{2.17}$$

The cost of D-STATCOM is calculated as follows:

$$C_\mathrm{DST} = K_\mathrm{DS} \times Q_\mathrm{DS} \times \frac{(1+B)^\mathrm{ND} \times B}{(1+B)^\mathrm{ND} - 1} \tag{2.18}$$

where Q_DS is the rated of the D-STATCOM in kVar, K_DS denotes the capital cost of D-STATCOM in \$/kVAR, ND is the lifetime of the D-STATCOM in years, and B is the asset rate of return of the D-STATCOM.

2.8 Photovoltaic Energy Systems

A stand-alone inverter is used in off-grid applications with battery storage. With backup diesel generators such as (PV–diesel hybrid power systems), the inverters may have additional control functions such as operating in parallel with diesel generators and bidirectional operation (battery charging and inverting). Grid-interactive inverters must follow the voltage and frequency characteristics of the utility-generated power presented on the distribution line. For both types of inverters, conversion efficiency is a very important consideration. Photovoltaic power systems can be classified as follows [77]:

- Stand-alone
- Hybrid
- Grid connected

2.8.1 Solar Photovoltaic

Solar PV technologies use some of the properties of semiconductors to directly convert sunlight into electricity. The advantages are that these technologies are characterized by zero emissions, silent operation, and a long-life service [78, 79]. They also require low maintenance and no fuel costs. In addition, solar energy is redundant and inexhaustible. However, it is weather-dependent, intermittent, and unavailable during the night. Given a high PV penetration level together with demand variations, power distribution systems would experience power fluctuations along with unexpected voltage rise, high losses, and low-voltage stability. Another drawback is that PV technologies require a high-capital investment cost [79].

The basic element of the PV conversion system is the PV cell, which is a just simple P-N junction. The equivalent circuit of the PV cell based on the well-known single-diode model is shown in Fig. 2.5. It includes the current source (photocurrent), a diode (D), series resistance (R_s) that describes the internal resistance to flow of current, and parallel resistance (R_{sh}) that represents the leakage current. The current-voltage (I-V) characteristics of the PV cell can be expressed as follows [45, 80, 81] (Fig. 2.6):

$$I = I_{ph} - I_s\left\{\exp\left[\frac{q(V + IR_s)}{\text{AKT}}\right] - 1\right\} - \left(\frac{V + IR_s}{R_{sh}}\right) \tag{2.19}$$

The light generated current (I_{ph}) mainly depends on the solar irradiance and working temperature of PV cell, which is expressed as follows [82, 83]:

$$I_{ph} = [I_{sc} + K_i(T - T_{ref})].\left(\frac{G}{1000}\right) \tag{2.20}$$

The PV saturation current (I_s) varies as a cubic function of the PV cell temperature (T), and it can be described as follows:

$$I_s = I_{rs}\left(\frac{T}{T_{ref}}\right)^3 \exp\left[\frac{qE_g}{KA}.\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{2.21}$$

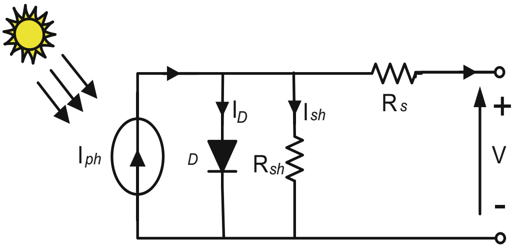


Fig. 2.5 Equivalent circuit of the PV cell

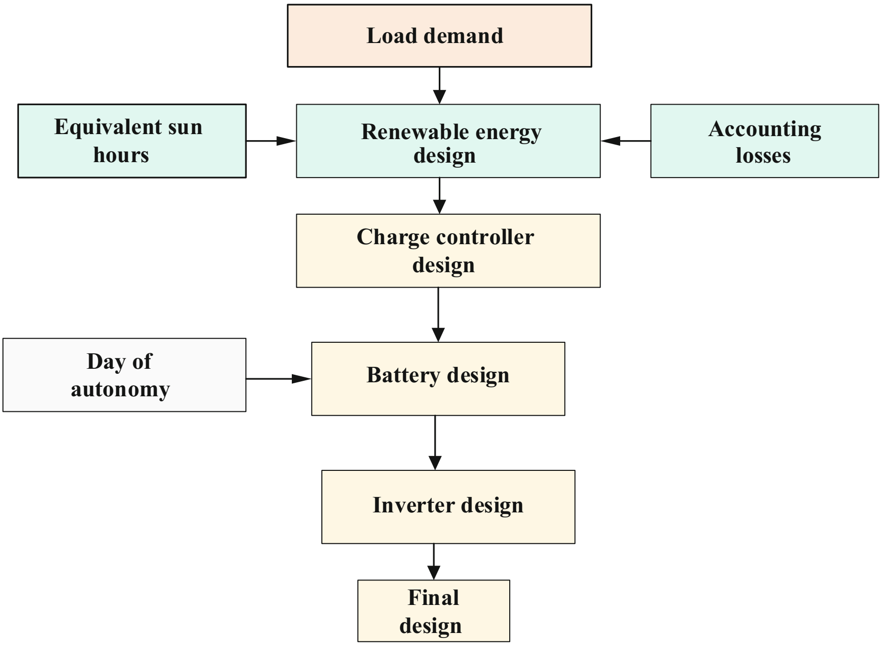


Fig. 2.6 A flowchart to design a stand-alone system

The reverse saturation current (I_{rs}) can be approximately obtained as follows:

$$I_{rs} = \frac{I_{sc}}{\left[\exp\left(\frac{qV_{oc}}{N_{ser}.\mathrm{K.A.T}}\right) - 1\right]} \tag{2.22}$$

where

I and V are output current and voltage of PV cell respectively,
I_s is the reverse saturation current of diode, and
I_{ph} is the current generated by the incidence of light.
R_s and R_{sh} are series and parallel resistances of PV cell, respectively,
The photocurrent ,I_{ph}, is a function of temperature and solar insolation.

Example 2.1
A stand-alone system using PV array, 250 Watt and parameters are

1. Load demand
   Load demand = 100 kW
2. Day of autonomy
   Day of autonomy = 2 days of battery

3. Losses

   Inverter efficiency = 90%

Efficiency cabal + charge controller + battery = 85%
System load $\frac{100\text{kW}}{0.9}$ /0.85 =130.72 kWh

Equivalent sun hours

Rate of Sohag City the sun of 5 hours/day

PV array design

Find the number of panels, maximum current parallel, charge controller, battery capacity, and minimum Cbatt?

Solution Minimum *W*p = $\frac{130.72\text{kwh/day}}{5\text{h/day}}$ = 26.14 kW

Number of panels = Minimum *W*p/capability one
Number of panels = 26.4 kW/250 W = 104 panels

Maximum current parallel

*I*max = 8.52 × 104 = 886.08 A
*V*max = 37.22 × 104 = 3870.88 V

Charge controller

Operation voltage = 12 or 24 V
Depth of charge = 60%
Battery voltage = 12 or 24 or 36 ....
Battery capacity = 450 Ah

Battery design

Minimum Cbatt = total energy demand/depth of charge × operational voltage of the system × 2 days
Minimum Cbatt = $\frac{130.72\text{kwh}}{0.6 \times 24}$ × 2 = 18155.56 Ah
Number of batteries in series = $\frac{24v}{12v}$ = 2 batteries
Number of battery in parallel = 18155.6 Ah/450 Ah$\frac{18155.6\text{Ah}}{200\text{Ah}}$ = 40 batteries
Number of batteries = 2 × 40 = 80 batteries

Inverter design

Minimum nominal power retting
100 kW/0.9 = 111 kW

2.8.2 Grid-Connected PV System

In a PV system, solar radiation is trapped and converted into electric power. PV cells are exposed to sunlight, the interior construction of PV cells can absorb photons, and then electrons are released. PV systems can be either on-grid or off-grid [84, 85]. The electric current by PV cells is always direct current (DC) in nature. It can be converted to alternative current (AC) by an electronic device inverter. There are four different topologies of PV inverter to be connected to the grid: (1) multi-string topology, (2) centralized topology, (3) string topology, and AC module topology [86]. It illustrated the PV system connection with the mesh power system. In this chapter, the PV-DG is modeled in a power system either PQ node or PV note. At the same time, it presents the modeling of the output power of the PV system based on solar irradiance [86] (Fig. 2.7).

Example 2.2
A grid-connected system using PV array 250 Watt and parameters are

Insolation = 1000 W/m^2
Efficiency PV = 20%
Efficiency inverter = 90%
Efficiency cable = 98%
Load demand = 100 kW

Equivalent sun hours

Rate of Sohag City the sun of 5 hours/day

Losses

System load = $\frac{100 \text{ kw}}{0.9}/0.98 = 113.37$ kWh

PV array design

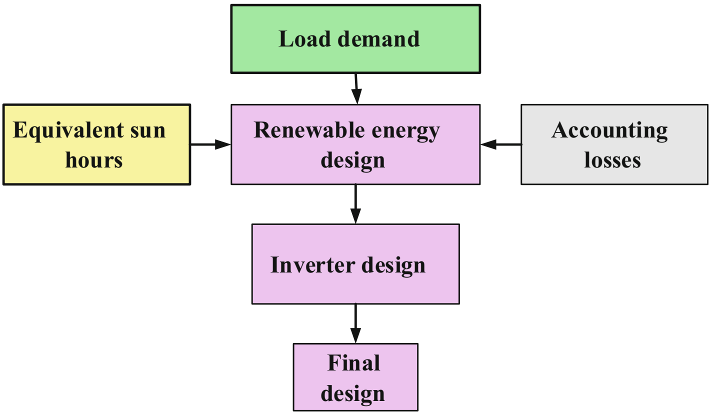


Fig. 2.7 A flowchart to design a grid-connected system

Find the number of panels, maximum current parallel, charge controller, battery capacity, and minimum Cbatt?

Solution Minimum $Wp = \frac{113.37\text{kwh/day}}{5\text{h/day}} = 22.67\ \text{kW}$

Number of panels = Minimum Wp/capability one
Number of panels = $\frac{22.67\text{kw}}{250\text{w}} = 100$ panels

Maximum current parallel

$I\text{max} = 8.52 \times 100 = 852\ \text{A}$
$V\text{max} = 37.22 \times 100 = 3722\ \text{V}$

Inverter design

Minimum nominal power retting
100 kW/0.9 = 111 kW

2.9 FACTS Devices

A flexible AC transmission system refers to a system consisting of power electronic devices along with power system devices to enhance the control and stability of the transmission system and increase power transfer capabilities. With the invention of the thyristor switch, the door was opened to develop of power electronics devices known as (FACTS) controllers. Basically, the FACTS system is used to provide the ability to control the high-voltage side of the network by integrating power electronic devices to provide inductive or capacitive power in the network [89].

The development of FACTS in the power transmission system has led to many applications of these controllers not only to improve various stability problems but also to provide the operating flexibility of power systems. There are different types of FACTS devices available for this purpose, specifically in the following subsections; concept of these FACTS devices is presented [90].

2.9.1 Types of FACTS Controllers

The system is based on electronic energy and other fixed equipment that provides control one or more of the AC transmission parameters. FACTS controllers can be categorized as:

- Shunt controller connected
- Series connected controller

- Combined series of controllers
- Combined shunt-series controllers

2.9.2 Shunt Compensation

The reactive current is injected into the line to maintain the voltage magnitude. The active power of the transmitter is increased, but you must provide more reactive power as described in Fig. 2.8.

2.9.3 Series Compensation

FACTS to series compensation modify line impedance: X is reduced to increase the active power that can be transferred. However, a more reactive power force should be provided in Fig. 2.9.

2.9.4 PV-DG Operation Modes

Depending on the type, electric machine of DG, and utility interface (direct or indirect) used for a connection to the power system, all DGs have to be models either as PQ (power-controlled) node or PV (voltage-controlled) node power flow

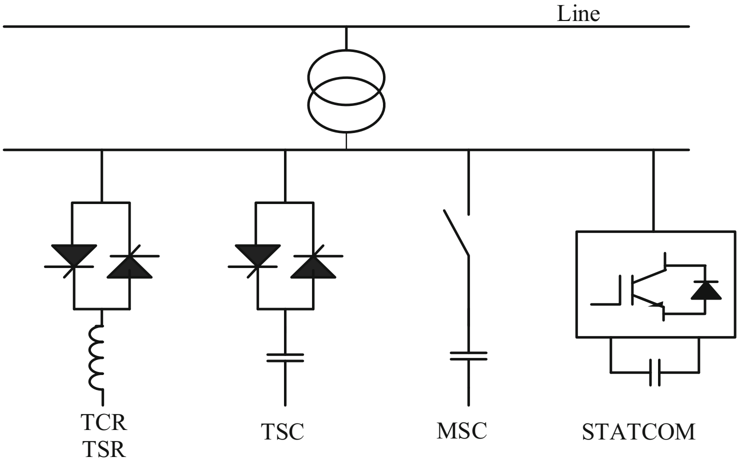


Fig. 2.8 Examples of FACTS to shunt switcher

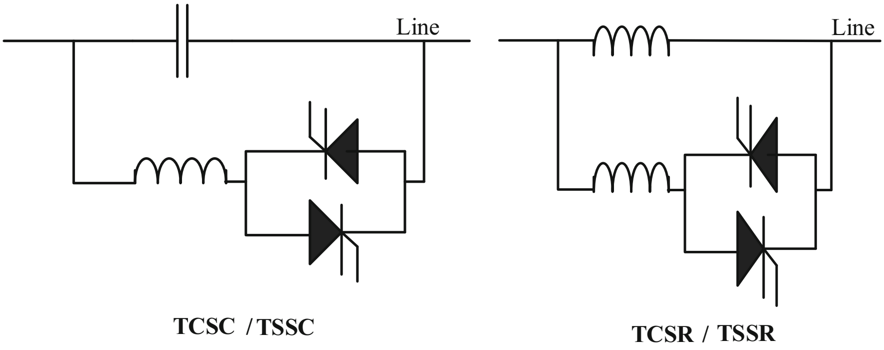


Fig. 2.9 Examples of FACTS to series switcher

studies [91]. PV-DG is installed to the power system via a power electronic interface. Based on the control mode of the electronic device, the PV-DG model is determined.

In the case of controlling P and V independently, the PV DG model is set to PV node. On other hand, the PV-DG model is a PQ node when P and Q are controlled independently [92]. In the case of the PQ node, the PV-DG behaves as a negative load which does not make any obstacle to power flow. Meanwhile, PV-DG can operate as the PV node which requires an iterative procedure to keep specified voltage magnitude and monitor DG reactive power limits. Therefore, some means should be considered [93–95].

2.10 D-FACTS Devices

Depending on the type, electric machine of DG, and utility interface (direct or indirect) used for a connection to the power system, all distributed flexible AC transmission system (D-FACTS) devices or “smart wires” change the effective line impedance of the transmission line on which they are installed. The simulator supports the response of D-FACTS devices responds based on online current. This functionality is described in [96]. The ability to effectively control power flow in a network can allow better utilization of the existing network by routing power flow away from overloaded lines. The problem of power flow control is even more compelling when considering the continually changing network topology and the need to remain secure under contingency conditions. Also, studies indicate that transient stability and dynamic stability can be improved when reactive compensation is available and can be varied rapidly by electronic control [97].

System benefits resulting from power flow control have been the motivating factors for the use of flexible AC transmission system (FACTS) devices since the time of their development. More recently, distributed flexible AC transmission system (D-FACTS) devices [96] such as the distributed static series compensator (DSSC) have been designed to address power control types of problems. D-FACTS devices attach directly to transmission lines and can be used to dynamically control effective line impedance. Also, D-FACTS devices are smaller and less expensive than traditional FACTS devices which may make them better candidates for wide-scale deployment [98].

The FACTS devices are used for maintaining, either supporting or preventing, raising the voltage by supplying or absorbing the reactive power, but not exclusively for the improvement of the quality of the supply. The D-FACTS devices are exclusively for the improvement of the quality of the supply. Widespread use of conventional FACTS controllers has not extensively occurred due in part to size, expense, and installation effort. The use of D-FACTS devices may facilitate the realization of a comprehensively controllable power system. Large-scale power flow control may finally be achievable [98].

A D-FACTS device changes the effective line impedance actively by producing a voltage drop across the line which is in quadrature with the line current. Thus, a D-FACTS device provides either purely reactive or purely capacitive compensation. D-FACTS devices do not change the line's resistance at all since doing so would imply the ability of the device to create real power. The impact on the system caused by D-FACTS devices on different lines working together can be coordinated to achieve some desired control objective. D-FACTS devices may be configured to operate autonomously in certain situations such as during transients, faults, etc. [98–101].

Distributed FACTS devices:

- Capacitive or inductive
- Distributed static series compensator (DSSC)
- Distributed series reactor (DSR)

Synchronous voltage source improved operation of distribution networks with the use of D-FACTS device.

2.11 Integration of DGs with Distribution Networks

Green energy sources, such as hydroelectric power, wind turbine and solar energy do not emit smoke or create pollution when they are used [3].

With the increasing efforts toward electricity generation from green energy sources, there is a need to integrate the distributed energy resources with the power system, which may be integrated with the placement of DGs and D-FACTS devices at the suitable locations [100–104].

2.12 Power Quality

The design of electrical power supply systems is a compromise between the interests of consumers – reliability and quality of supply – and those of the supply industry – realistic investment levels and operating costs. The flexibility allowed to deviate from "perfect" power quality should be used to allow cheaper and simpler supply systems; it should not be wasted by permitting poor maintenance and operating procedures to compromise reliability [105].

Consider electric energy as a product: it is generated, transmitted, distributed, and sold to customers. The end-user converts the electric energy into other forms such as mechanical, thermal, and light energy. The users of electric energy expect a reasonable degree of reliability and quality of service. In technical terms, the following conditions are required to ensure customer satisfaction [106].

The electric energy must be continuously available (reliable supply).

The voltage supply must alternate at a constant frequency with a sinusoidal waveform and a constant magnitude.

The voltage magnitude must be within the range recommended by the equipment manufacturer.

In three-phase systems, there must be perfect symmetry: The three voltages must be identical sinusoids shifted 1,200 with respect to each other.

2.13 Power Quality Disturbances Classification

The effects of power disturbances vary from one piece of equipment to another and with the age of the equipment. Equipment that is old and has been subjected to harmful disturbances over a prolonged period is more susceptible to failure than new equipment. To classify different types of power quality disturbances, the characteristics of each type must be known. In general, power quality disturbances are classified into two types: steady-state and non-steady-state. This classification is done in terms of the frequency components which appear in the voltage signals during the disturbance, the duration of the disturbance, and the typical voltage magnitude. These disturbances are mainly caused by [107]:

- External factors to the power system: for example, lightning strikes cause impulsive transients of large magnitude.
- Switching actions in the system: a typical example is capacitor switching, which causes oscillatory transients.
- Faults which can be caused, for example, by lightning (on overhead lines) or insulation failure (in cables).
- Voltage dips and interruptions are disturbances related to faults.
- Loads which use power electronics and introduce harmonics to the network.

2.14 Power Quality Issues

A recent study of power quality experts indicates that 50% of all power quality issues are related to grounding, earth bonds, neutral to ground voltages with earth loops, ground current, or other ground-associated issues. Equipment that is powered by electricity or related to it is affected by the power quality. Identification of the issues requires sophisticated electronic testing equipment. The following symptoms are indicators of power quality issues [108]:

- A piece of equipment is malfunctioning at the same time of day.
- Trip circuit breakers without being overloaded.
- Equipment failure during thunderstorms.
- Automated systems shall cease for no apparent reason [109].

In the power system, the power quality indicates a high degree of electrical service. The need for end-user equipment determines the desired power quality. In general, power quality refers to the maintenance of a sinusoidal waveform for voltage and frequency voltages, the concept of powering, and the grounding of sensitive equipment in an appropriate manner to operate the equipment. Some common power quality problems include voltage drops (Sag), voltage amplification, interruptions, transient or voltage flicker, voltage unbalancing, harmonics, DC offset, notches, and noise, etc. [110].

The problems of power quality have increased significantly according to power electronic-based devices in the electrical distribution system. D-STATCOM is a promising shunt-connected custom device designed to mitigate power quality problems. Investigation on the SRF-based D-STATCOM system is performed with the grid-connected PV system using a fuzzy logic controller via the PI controller for reactive power management. Distribution static synchronous compensator (D-STATCOM) is an inverter-based power-quality conditioner connected in shunt with an AC system. It is used to correct power factor, load balancing, voltage regulation, and harmonic filtering in distribution systems [111].

The distribution system is characterized by poor power quality due to the lack of sufficient reactive energy during the state of stability and dynamism. Because of the extensive use of automatic, this is addressed by modeling and analyzing dedicated power controllers and electronic power-based equipment designed to enhance the reliability and quality of power flow in low-voltage distribution networks using D-STATCOM. A new PWM-based control system that requires only voltage measurements is operation, and the proposed D-STATCOM control mode is displayed [112]. This proposes the power quality improvement of stand-alone hybrid power generation employing solar power and wind power using FACTS devices. The hybrid power generation system, which uses natural energy, will integrate the protection of the global environment into isolated and rural areas without any dependence on the commercial power system. This shows the use of the FACTS device toward improving the power quality by removing the harmonics in the voltage [113].

2.15 Classification of Power Quality Disturbances

Power quality phenomena classification and characterization are shown in the chart of Fig. 2.10.

2.15.1 *Transient Power Quality Disturbance*

Transient PQ disturbances are momentary transient disturbances are classified to.

Impulsive transient PQ disturbances (Fig. 2.11) which are sudden, non-power frequency change in the steady-state voltage or current waveforms with unidirectional polarities characterized by rising and decay times mainly caused by lightning.

Oscillatory transient PQ disturbances (Fig. 2.12) are sudden, non-power frequency change in the steady-state condition of voltage, current, or both, including positive and negative values, characterized by its spectral contents, duration, and

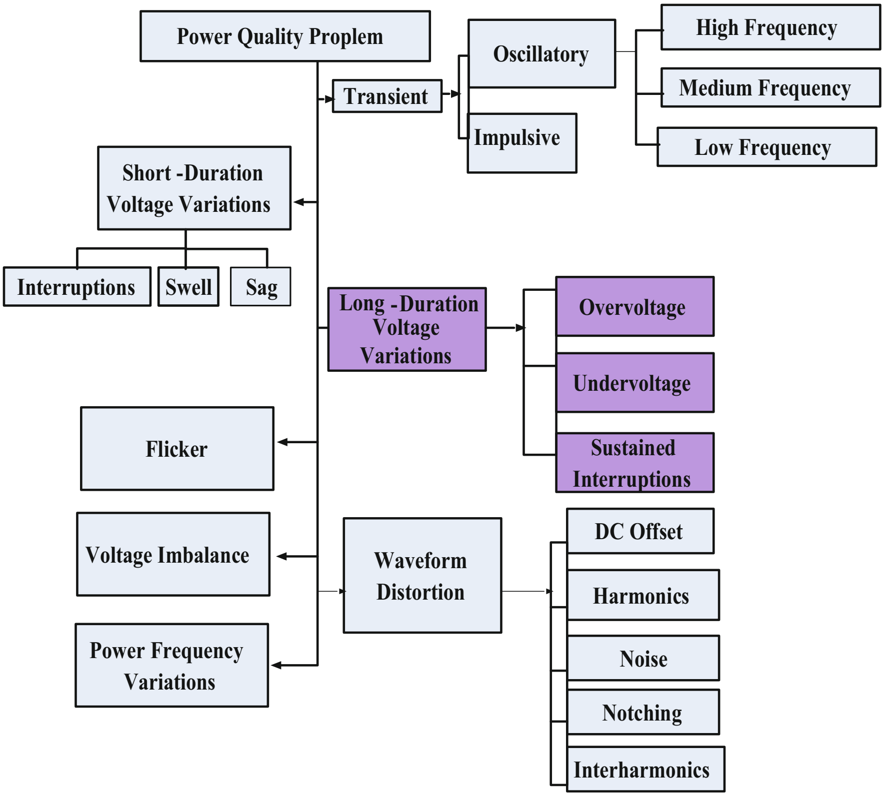


Fig. 2.10 Power quality disturbances

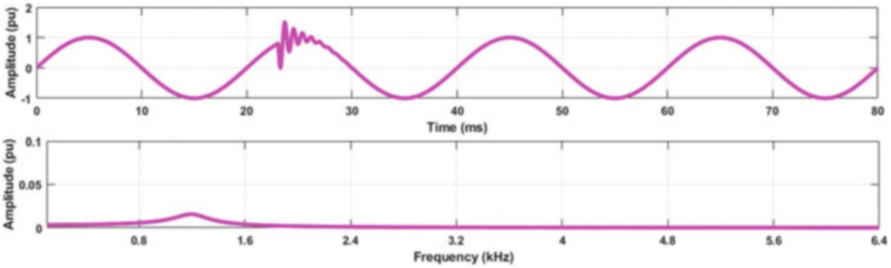


Fig. 2.11 Impulsive transient PQ disturbance

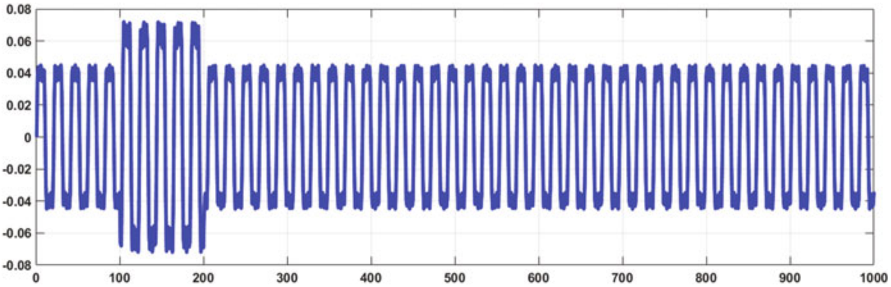


Fig. 2.12 Oscillatory transient PQ disturbance

magnitude [113]. Based on spectral contents, oscillatory transients can be classified into high-, medium-, and low-frequency oscillatory transients. The oscillatory transient may be caused by power electronic commutation (several kHz), capacitor bank energization on distribution system (low frequency).

2.15.2 *Short-Duration Voltage Variations*

Depending on duration of voltage variations, short-duration voltage disturbances, Fig. 2.13, can be classified into three categories:

Voltage sag: this is a drop in voltage (between 10% and 90%) for a few cycles (1–30). This is caused by a fault in the power system in remote locations. Voltage sag can also be the result of a lightning strike that operates a circuit breaker or a reclosure, which recloses instantaneously (3–10 cycles). Also, motors – both constant-speed and ASD – may cause voltage sag (for about 65% voltages) [113].

Voltage swells: this is an increase in the voltage between 1.1 and 1.8 p.u. at the power frequency for a short period (1–30 cycles). The cause can be changed in system loading (a large load is dropped), switching on of a capacitor bank, etc. The lights blink as an indication of swells.

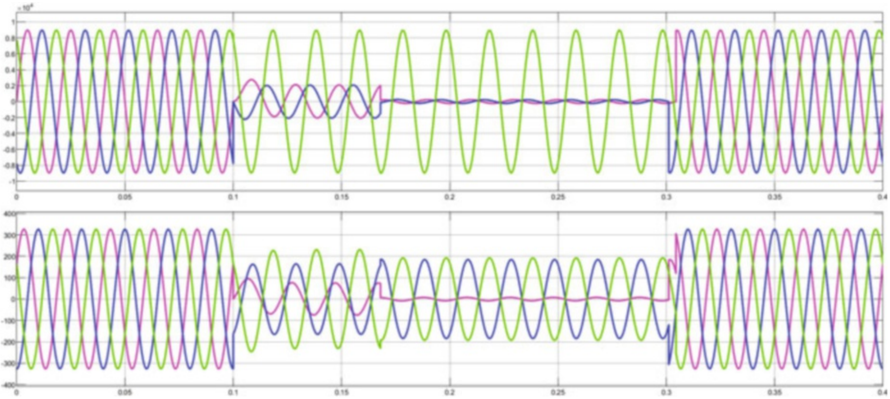


Fig. 2.13 Short-duration voltage disturbances

Interruptions: which are temporary and momentary interruptions that occur when the supply voltage decrease less than 10% of its nominal value up to a period not larger than 1 minute.

2.15.3 Long-Duration Voltage Variations

Duration of long-duration voltage disturbances is generally larger than 1 minute. These PQ disturbances can be classified to:

Undervoltage: is a drop in voltage below the standard voltage tolerance (±5%). Most equipment will operate in the range of ±10% for a short period without damage. Starting large motors may cause the voltage to drop close to 10% [108].

Overvoltage: is an increase in voltage above the standard voltage tolerance (±5%). Over voltages can be a result of erroneous system operation, line-to-ground faults, or switching of major system components.

Sustained interruptions: which are interruptions that occur when the supply voltage decreases less than 10% of its nominal value for a period larger than 1 minute [108].

Voltage imbalance: voltage imbalance is defined as the ratio of negative sequence voltage (and/or the zero-sequence voltage) to the positive sequence voltage. Voltage imbalance can result from unbalanced loads [113].

2.15.4 Waveform Distortion

The steady-state deviation of voltage and/or current waveforms from the pure sinusoidal power frequency waveforms is referred to as waveform distortion phenomena in Fig. 2.14. Waveform distortion PQ problem can be classified [114].

DC offset: is defined by the presence of a DC bias in the voltage and/or current waveforms. DC offset results from the operation of rectification equipment such as half-wave rectifiers. DC offset can cause saturation problems in transformers and machines [114].

Harmonics: are sinusoidal voltages and/or currents of frequencies that multiples of the fundamental system frequencies. The use of converters, nonlinear loads, etc. is the major source of harmonics [49].

Interharmonics: which are harmonics with frequencies that are not integer multiples of the fundamental frequency. Interharmonics can be caused by static frequency converters, cycle converters, and arcing devices.

Notching: is a periodic voltage disturbance caused by the normal operation of power electronic devices as the current is commutated from one phase to another Fig. 2.15 [49].

Electrical noise: is the distortion (not necessarily periodic) with broadband spectral contents lower than 200 kHz superimposed on the power system voltage and/or current waveforms. Switching radio transmitter and arcing industrial equipment can cause electrical noise [113].

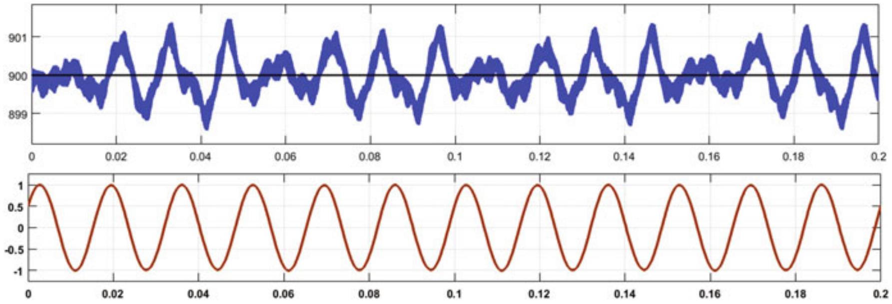


Fig. 2.14 Waveform distortion

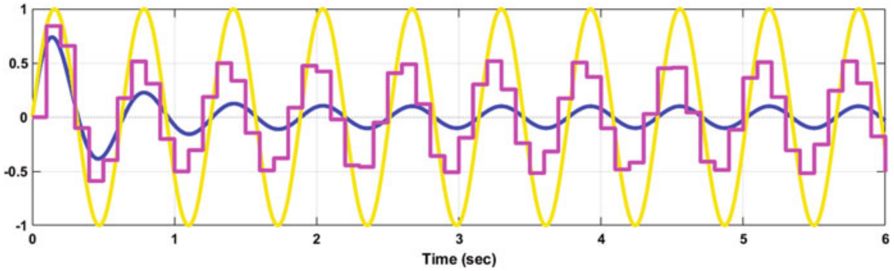


Fig. 2.15 Commutation notches

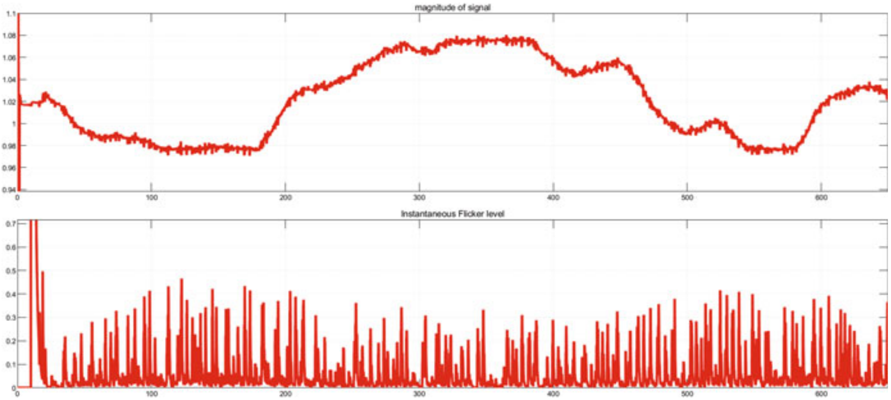


Fig. 2.16 Voltage fluctuations

2.15.5 *Flicker*

Flicker is the term used to define the fluctuations of voltage, Fig. 2.16, caused by loads that vary in frequency. Flicker is the perceptible change in the output of a source of light when there is a sudden change in the supply voltage (sag or swell). The voltage fluctuations cause light pulsations. If such disturbances are recurrent and the incremental change in the luminous flux is large enough, the flicker becomes annoying [115]. The eye–brain perception system has maximum sensitivity at about nine fluctuations per second (9 Hz). At this critical frequency, a voltage dip or swell of V as small as 0.5% is sufficient to cause end-user objections [115].

2.15.6 *Frequency Variations*

Power frequency variations are defined as the deviation of the power system fundamental frequency from its nominal value. Large load shedding or disconnection of large generators can cause frequency variations. Frequency deviation can affect the performance of electronic timers and also can reduce measuring equipment accuracy [115].

2.16 Questions

Define distributed generation?
Draw distributed electricity systems?
Mention the commercial and industrial sectors, distributed generation?
What are distributed generation applications?

What are distributed generation technologies?
Define distributed static compensator (D-STATCOM)?
What is the power quality impact of PV-DG?
Draw the schematic diagram of the D-STATCOM device?
Classify photovoltaic power systems?
What are the facts devices?
Mention the types of FACTS controllers?
Draw the examples of facts to shunt switcher?
Mention the D-FACTS devices?
Why there are power quality issues?
What is power quality?
Classify power quality disturbances?