9.1. Resurgence of Distributed Generation (DG)

- The demand of power is escalating in the world of electricity. This growth of demand triggers a need of more power generation. DG uses smaller-sized generators than does the typical central station plant. Distributed generators are small scale generators located close to consumers; normally Distributed Generators are of 1 kW to 100 MW.

  Definition of DG

  Distributed generation in simple term can be defined as a small-scale generation. It is active power generating unit that is connected at distribution level.
- IEEE defines the generation of electricity by facilities sufficiently smaller than central plants, usually 10 MW or less, so as to allow interconnection at nearly any point in the power system, as Distributed Resources.
- Electric Power Research Institute (EPRI) defines distributed generation as generation from a few kilowatts up to 50 MW.
- International Energy Agency (IEA) defines DG as "Power generation equipment and system used generally at distribution levels and where the power is mainly used locally on site".
- The International Council on Large Electricity Systems (CIGRE) defines DG as generation that is not centrally planned, centrally dispatched at present, usually connected to the distribution network, and smaller than 50-100 MW.
- These generators are distributed throughout the power system closer to the loads. The DG penetration in the grid poses new challenges and problems to the network operators as these can have a significant impact on the system and equipment operations in terms of steady-state operation, dynamic operation, reliability, power quality, stability and safety for both customers and electricity suppliers. However as we are only concerned with power quality of the primary and secondary distribution system, we will only consider generator sizes less than 10MW.
- Generators larger than this are typically interconnected at transmission voltages where the system is designed to accommodate many generators. The normal distribution system delivers electric energy through wires from a single source of power to a multitude of loads. Thus, several power quality issues arise when there are multiple sources.

  Advantages of DG
- The customers get benefit of backup generation improving the reliability of the power supply, possibly at a lower cost.
- The technology can be effectively used for combined heat and power applications.
- DG can enhance the generation capacity of a power system without having an adverse impact on the environment.

9.2. DG Technologies

- Due to maturing technologies and increasing size of DGs, which play a significant and topical phenomenon in power system, there is as yet no universal agreement on the definition of DGs. These are also known as embedded generations or dispersed generations. Current definition of DG is very diverse and range from 1kW PV installation, 1 MW engine generators to 1000 MW offshore wind farms or more.

- The some of the popular DG technologies are listed below:
  1. Reciprocating Diesel or Natural Gas Engines
  2. Micro-Turbines
  3. Combustion Gas Turbines
  4. Fuel Cells
  5. Photovoltaic (PV) system
  6. Wind Turbines
- The detailed discussion of application, recent trends, benefits and challenges of DG is given in ref. Table 9.1 provides a brief overview of the most commonly used DG technologies and their typical module size.

Table 9. 1 Distributed generators with available size

Sr. No.	Technology	Typical available size power module
1	Combined cycle gas turbine	35-400 MW
2	Internal combustion engines	5 kW – 10 MW
3	Combustion turbine	1-250 MW
4	Micro-turbines	35 kW-1 MW
5	Fuel-cells, Phos. Acid	200 kW-2 MW
6	Fuel-cells, Molten Carbonate	250 kW-2 MW
7	Fuel-cells, Proton Exchange	1-250 kW
8	Fuel-cells, Solid oxide	250 kW-5MW
9	Battery storage	0.5-5 MW
10	Small Hydro	1-100 MW
11	Micro hydro	25 kW-1 MW
12	Wind turbine	200 W-3 MW
13	PV arrays	20 W-100 kW
14	Solar Thermal, Central receiver	1-10 MW
15	Solar Thermal, Lutz system	10-80 MW
16	Biomass Gasification	100 kW-20 MW
17	Geothermal	5-100 MW
18	Ocean Energy	0.1-1 MW

- The technologies 10-18 can be considered as renewable DGs. The other technologies could also be called renewable DG if they are operated with bio-fuels. Similarly, to the centralized generation, the following three generation technologies are normally used for distributed generation: synchronous generator, asynchronous generator, and power electronic converter interface.

9.2.1 Wind Energy

- India ranks fifth amongst the wind-energy producing countries of the world after Germany, Spain, USA and China. Estimated potential is around 45000 MW at 50 m above ground level. Wind farms have been installed in more than 9 States. More than 95% of installed capacity belongs to private sector in seven States. A good number of wind turbine manufacturers are active in India and producing Wind Electric Generators

(WEGs) of rating 225 kW to 2100 kW. A large number of water pumping windmills and small aero-generators have been installed in the country. wind-solar and wind-diesel hybrid systems have also been installed at a few places. The Ministry of New & Renewable Energy (MNRE), Govt. of India has established a centre for wind energy technology at Chennai with field test station at Kayathar to act as technical focal point for wind power development in the country. Financial assistance for renewable source of energy is available through Indian Renewable Energy Development Agency (IREDA), a supporting arm of MNRE.

9.2.2 Solar Energy

- India receives solar energy equivalent to over 5,000 trillion kWh per year. The daily average solar energy incident varies from 4 - 7 kWh per square meter of the receiving area depending upon the location. A target of 50 MW has been set for solar power generation during the eleventh five year plan, which is likely to be achieved.
- A total of 33 grid interactive solar photovoltaic power plants have been installed in the country with financial support from the Government. These plants, with aggregate capacity of 2.12 MW, are estimated to generate about 2.55×10^6 kWh of electricity in a year. In addition, around 1.45×10^6 decentralized off-grid solar photovoltaic systems aggregating to about 125 MW capacities have been installed in the country, which is capable of generating about 150×10^6 kWh in a year. Further, a collector area of about 2.15×10 square meters has been installed for solar water heating applications. Typically, a solar water heating system with 2 square meters of collector area can generate energy equivalent to up to 1500 kWh of electricity when the system is used for about 300 days in a year.

9.2.3 Biomass

- A target for addition of 1700 MW capacity, consisting of 500 MW of biomass power projects and 1200 MW of bagasse cogeneration projects has been proposed during XI plan period i.e. up to 2012. A cumulative biomass power potential of about 18,000 MWe from the surplus of agro residues have been estimated in the country. The States of Andhra Pradesh, Assam, Bihar, Chhattisgarh, Gujarat, Haryana, Himachal Pradesh, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal are having potential for setting up biomass based power projects of 100 MW or above. The biomass power potential in the identified districts of the above States ranges from 10 MW to 100 MW. Sugar mills having crushing capacity of 2500 tons of cane crushed per day in the States have an estimated potential of about 5000 MW surplus power generation through optimum bagasse based cogeneration.

9.2.4 Small Hydro Power

- Six hundred eight small hydro power projects (up to 25 MW capacity) with an aggregate capacity of 2015 MW have been set up in the country. The annual estimated generation from these projects is 4028×10^6 kWh per year. A target of adding 1400 MW from small. hydro power has been planned during the 11^{th} Five Year Plan.

9.3. Interface to the utility

- Here we are only concerned about the impact of distributed generation on power quality. While the energy conversion technology may play some role in the power quality, most power quality issues relate to the type of electrical system interface.
- Some notable exceptions include:
  (a) The power variation from renewable sources such as wind and solar can cause voltage fluctuations.
  (b) Some fuel cells and micro turbines do not follow step changes in load well and must be supplemented with battery or flywheel storage to achieve the improved reliability expected from standby power applications.
  (c) Misfiring of reciprocating engines can lead to a persistent and irritating type of flicker, particularly if it is magnified by the response of the power system.
- The main types of electrical system interfaces are synchronous machines, asynchronous (induction) machines and electronic power inverters.

  Synchronous Machines: Some actual examples of unexpected consequences are:

  1. The harmonic voltage distortion increases to intolerable levels when the generator is attempting to supply adjustable-speed-drive loads.

  2. There is not enough fault current to trip breakers or blow fuses that were sized based on the power system contribution.

  3. The voltage sag when elevator motors are being started causes fluorescent lamps to extinguish. Generators must be sized considerably larger than the load to achieve satisfactory power quality in isolated operation.

- ***Asynchronous (induction) machines*:** Induction generators are induction motors that are driven slightly faster than synchronous speed. They require another source to provide excitation. The requirements for operating an induction generator are essentially the same as for operating an induction motor of the same size. The chief issue is that a simple induction generator requires reactive power (vars) to excite the machine from the power system to which it is connected.

  To supply the reactive power locally, power factor correction capacitors are added. While this works well most of the time, it can bring about another set of power quality problems. One of the problems is that the capacitor bank will yield resonances that coincide with harmonics produced in the same facility. Another issue is self-excitation. An induction generator that is suddenly isolated on a capacitor bank can continue to generate for some period of time. This is an unregulated voltage and will likely deviate outside the normal range quickly and be detected.

- ***Electronic power inverters:*** All DG technologies that generate either dc or non–power frequency ac must use an electronic power inverter to interface with the electrical. The early thyristor-based, line-commutated inverters quickly developed a reputation for being undesirable on the power system. The line-commutated inverters produce harmonic currents in similar proportion to loads with traditional thyristor-based converters. Besides contributing to the distortion on the feeders, one fear was that this type of DG would produce a significant amount of power at the harmonic frequencies.

Such power does little more than heat up wires. To achieve better control and to avoid harmonics problems, the inverter technology has changed to switched, pulse-width modulated technologies.

9.4. Power Quality Issues

- A major issue related to interconnection of distributed resources onto the power grid is the potential impacts on the quality of power provided to other customers connected to the grid.

9.4.1 Voltage Regulation

- Over-voltages due to reverse power flow: If the downstream DG output exceeds the downstream feeder load, there is an increase in feeder voltage with increasing distance. If the substation end voltage is held to near the maximum allowable value, voltages downstream on the feeder can exceed the acceptable range.
- Interaction with load tap changers (LTC) and static voltage regulators (SVR) controls: The presence of DG can cause localized changes in flow patterns, which are not reflective of the general trend on the feeder. As a result, LTC or SVR can be set such that a good voltage profile may not be obtained.

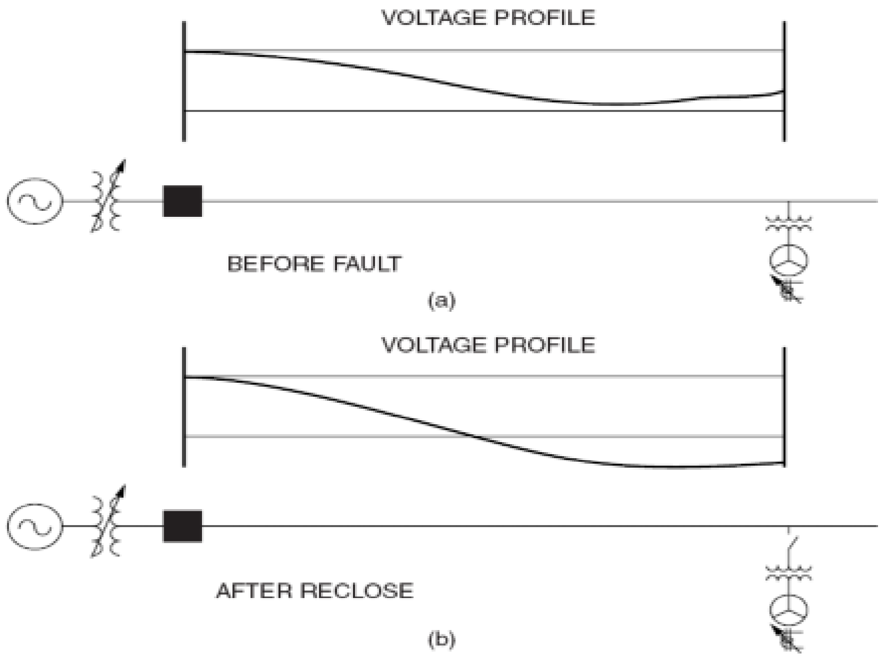

Figure 1 Voltage profile change when DG is forced off to clear faults

- Figure 1 illustrates one voltage regulation problem that can arise when the total DG capacity on a feeder becomes significant. This problem is a consequence of the requirement to disconnect all DG when a fault occurs.
- Figure 1a shows the voltage profile along the feeder prior to the fault occurring. The intent of the voltage regulation scheme is to keep the voltage magnitude between the two limits shown. In this case, the DG helps keep the voltage above the minimum and, in fact, is large enough to give a slight voltage rise toward the end of the feeder.
- When the fault occurs, the DG disconnects and may remain disconnected for up to 5 min. The breaker recloses within a few seconds, resulting in the condition shown in Fig. 1b.

The load is now too great for the feeder and the present settings of the voltage regulation devices.

- Therefore, the voltage at the end of the feeder sags below the minimum and will remain low until voltage regulation equipment can react. This can be the better part of a minute or longer, which increases the risk of damage to load equipment due to excessively low voltages.

 Solutions include:

 1. Requiring customer load to disconnect with the DG. This may not be practical for widespread residential and small commercial loads. Also, it is difficult to make this transition seamlessly and the load may suffer downtime anyway, negating positive reliability benefits of DG.

 2. Installing more voltage regulators, each with the ability to bypass the normal time delay of 30 to 45 s and begin changing taps immediately. This will minimize the inconvenience to other customers.

 3. Allow DG to reconnect more quickly than the standard 5-min disconnect time. This would be done more safely by using direct communications between the DG and utility system control.

 4. Limit the amount of DG on the feeder.

9.4.2 DG Grounding Issue

- A grid-connected DG, whether directly or through a transformer, should provide an effective ground to prevent un-faulted phases from over-voltage during a single-phase to ground fault. Proper grounding analysis of DG will ensure compatibility with grounding for both the primary and secondary power systems.

 This analysis must consider

 (1) the generator-winding configuration (or inverter arrangement),

 (2) its grounding point,

 (3) the interface transformer configuration, and

 (4) grounding of both the primary and secondary power systems to which the DR is connected.

 Solutions Include:

Table 9.2 Grounding recommendations for distributed sources

Design of primary distributed system	**Design of secondary system**	**DR Grounding**
Three-wire, ungrounded system or high-impedance, grounded system	4-wire, grounded	DR should be ungrounded or high-impedance grounded w.r.t. the primary and effectively grounded w.r.t. the secondary system
	3-wire, ungrounded	DR should be ungrounded or high-impedance grounded with respect to primary and secondary system
Four-wire, multi-grounded	4-wire, grounded	DR should be effectively

neutral system		grounded w.r.t. the primary and secondary system
	3-wire, ungrounded	Dr should be effectively grounded w.r.t. the primary system and ungrounded or high-impedance grounded w.r.t. the secondary system

9.4.3 Harmonic Distortion

- Voltage harmonics are virtually always present on the utility grid. Nonlinear loads, over electronic loads, and rectifiers and inverters in motor drives are some sources that produce harmonics. The effects of the harmonics include overheating and equipment failure, faulty operation of protective devices, nuisance tripping of a sensitive load and interference with communication circuits.
- All power electronic equipments create current distortion that can impact neighbouring equipment. DG like PV, fuel cells are likely to introduce harmonics problem in the system. Harmonics from DG come from inverters and some synchronous machines. The PWM (pulse width modulation) switching inverters produce a much lower harmonic current content than earlier line-commutated, thyristor-based inverters.
- One new distortion problem that arises with the modern inverters is that the switching frequencies will occasionally excite resonances in the primary distribution system. This creates non-harmonic frequency signals typically at the 35th harmonic and higher riding on the voltage waveform. This has an impact on clocks and other circuitry that depend on a clean voltage zero crossing. A typical situation in which this might occur is an industrial park fed by its own substation and containing a few thousand feet of cable. A quick fix is to add more capacitance in the form of power factor correction capacitors, being careful not to cause additional harmful resonances.

  Solutions include:

  1. Newer PWM inverters have lower current distortion
  2. Use non-resonant switching frequencies
  3. Use reactors in the neutral, or generators with a 2/3 coil winding pitch

9.4.4 Flicker

- Some energy source (e.g., wind turbine or fuel cell) has some mechanical (or chemical) fluctuations in power output and some electrical equipment (e.g., the dc bus and inverter) does not have sufficient energy storage to smooth out these fluctuations. This will result in fluctuations in the power delivered by a DG and can cause flicker in the power system in a fashion very similar to that caused by load fluctuations.

  Solutions include:

  1. Utility companies try to limit flicker so that it is at a level that cannot be perceived by the human eye. This is accomplished by designing the power system to be sufficiently robust so that smaller load variations do not create noticeable voltage variations.
  2. It is also controlled by imposing limits on the types of loads that are allowed to connect at various points on the system

3. When a larger DR unit is applied on a feeder, rapid response voltage regulators (static VAR compensators) or fast-response reactive compensation using inverter reactive-power capabilities can do mitigation of flicker.
4. Energy storage technologies can be applied to smooth the output fluctuations of solar and wind energy systems.

9.4.5 Islanding

- Refers to a condition in which distributed generation is isolated on a portion of the load served by the utility power system. It is usually an undesirable situation, although there are situations where controlled islands can improve the system reliability. Islands may be intentional or unintentional.
- If an island should occur, it should persist for only a very brief period, unless the aggregate real and reactive output of all the DG supporting the island is close to the load demand. Otherwise, island voltage and frequency will change rapidly and all the DG has to be shut down to prevent this.
- In case the DG in the distribution system is capable to meet the load demand, DG can be operated in the island mode and continue to energize the distribution system. But the major issues with this type of inadvertent islanding are:
  1. The voltage and frequency provided to other customers connected to the island are out of the utility's control, yet the utility remains responsible to those customers.
  2. Protection systems on the island are likely to be uncoordinated, due to the drastic change in short-circuit current availability.
- *Out-of-step reclosing:* Many utilities use an "instantaneous" reclosing practice, where breakers and circuit reclosers reenergize the protected circuit without any intentional delay and this could result in out of phase reclosing of the distribution system. As a result of out of phase reclosing:
  1. Large mechanical torques and currents are created, which can damage the generator or the prime mover.
  2. Transients are created which are potentially damaging to utility and other customer equipment.
  3. Out-of-phase reclosing, if it occurs at a voltage peak, will generate a very severe capacitive switching transient. In a lightly damped system, the crest over-voltage can approach three times rated voltage.
  Prevention:
  1. Inverter controls are designed to raise a rising frequency or lower a dropping frequency
  2. The power system frequency acts to correct the inverter frequency
  3. Without the power system to correct the frequency, the destabilizing signal in the inverter control quickly causes an over- or under-frequency condition, and frequency relays trip the inverter
  4. Load/generation imbalance relies on an intentional and significant difference between the DG output and the local load. DG is operated at constant power factor or constant reactive power, and not permitted to regulate voltage. When an island forms, the mismatch between the DG and the load will quickly cause detectable voltage and/or frequency variations

9.4.6 Protection System

- Tradition distribution systems were not designed to have active power generating units in them. Power is supplied by the transmission system and power flow is mainly unidirectional. But with the DG in the system, power flow can be bi-directional.
- Depending on characteristics of the network and DG, various other protection problems can arise. They are namely:
  1. False tripping of feeders (sympathetic hipping)
  2. Fuse coordinate with recloser fast-trip varies with DG operation
  3. Nuisance tripping of production units
  4. Blinding of protection
  5. Increased or decreased fault levels
  6. Unwanted islanding
  7. Prohibition of automatic reclosing
  8. Unsynchronised reclosing
  Solutions Include:
  1. Reduction of Reach: Adjust relay to increase reach. Add recloser to add another protection zone. Minimize DG contribution to ground faults.
  2. Sympathetic tripping: Directional relays, changes to circuit breaker settings.
  3. Defeat of fuse saving: Larger fuses, minimize DG contribution to ground faults.

9.5. Operating Conflicts

- DG output is varied according to the local load variation. DG power output can also be controlled independently of the local loading of the area. This control mode is implemented if DG operation follows price signal, which might or might not correspond to the local load variations, or DG follows the availability of natural resources, like solar or wind power.
- In this case, DG might adversely affect the voltage control functionality of the network by increasing the variations between the maximum and minimum voltage level, compared to a situation when DG is not available. Since the minimum voltage level could remain (usually at a high load, no DG situation) but the maximum voltage level could increase, e.g. in low load situations with DG operating at maximum production and at a unity power factor. Generally speaking, DG can provide some challenges to the traditional voltage, frequency and power control.
- Due to large penetration of DG, there is risk of control and stability issues. If a circuit breaker in a distribution system opens, it could results in an islanding of a DG unit. If the loss-of-mains is not detected by the DG unit, for example due to insufficient fault current, the DG unit will continue to operate.
- If the DG unit is able to match active and reactive power of the load in the islanded system precisely, then the islanded system could continue to operate without any problem. It is, however, very unrealistic that DG will exactly match the load in the system during the time the circuit breaker opens, hence large frequency or voltage variations will occur when the DG unit tries to supply load.

- Hence, most interconnection rules require a loss of-main detection system which automatically disconnects the DG unit in case of a loss of main and the unit remains disconnect until the grid is restored.
