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Review on distributed generation technology in power systems

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Abstract

The paper presents a comprehensive review of distributed generation integration in power systems. The paper gives detailed information about the distributed generation in eleven sections and some subsections. A brief introduction to power system operation is presented. In its distributed generation and its importance to the power system is described. The paper thoroughly defines distributed generation as far as power system is concerned. Impact and effects of distributed generation in the power system are well explained. The paper outlines classes, types, features, advantages, drivers, benefits, challenges, and application of distributed generation in the power system. The functional relationship between distributed generators and capacitors is given. Impacts, effects, and technologies of distributed generation in the power system are reported. Comparison between the two widely used renewable energy technologies for distributed generation is also included. The paper explains how distributed generation causes challenges to the protection of distribution networks. Voltage and frequency control with distributed generation penetration in the power system is part of this work. The information contained in this paper can be used as a foundation for many types of research concerning distributed generation.

Keywords: Review, distributed generation, renewable energy, planning and operation, power system

Introduction

Power system consists of three main areas namely generation, transmission, and distribution. A traditional power system consists of a power plant, a transmission grid, and a distribution system. Generation is responsible for the power production in a small or large amount. Electricity generation can be from renewable or nonrenewable sources such as such as coal, hydro, natural gas, nuclear, petroleum, sun, wind etc. Most power plants are usually located in remote areas a long distance from load centers. Power transmission refers to the transportation of generated electricity along a network of power lines. Distribution refers to the process of transporting energy to the customer (Dugan, 2009).

Due to increasing demand (Pillai, 2017), the transmission network is in need of major upgrades (Kersting, 2001) due to lost capability. Less transmission capability means that more generation resources would be required (Poli et al. 2007). Distributed generation (DG) is often used to offset transmission costs or other costs associated with major improvements to the power grid.

Distributed generation can be used in industries, commercial activities, residential or utility. Distributed generators can use either renewable or nonrenewable energy sources. The nonrenewable DG sources include fuel cells, diesel, micro-turbines or natural gas; while renewable DG sources include biomass, photovoltaic and wind. The distributed generator can be operated as a primary generator, standby generator, or a source for reactive power. The owners and operators of distributed generators can be placed into one of two categories: non-utility or utility.

In addition, several recent developments have encouraged the entry of power generation and energy storage at the distribution level (Chiradeja, 2005). Some of the major ones are retail competition brought upon by utility structuring, customers demanding customized power supplies to suit their needs, the need to defer large capital investments in building new central-station power plants and transmission lines, advent of several technologies with reduced environmental impacts and high conversion efficiencies, advent of efficient and cost-effective power electronic interfaces to improve reliability and power quality and the ability to effectively control a number of components and subsystems using state-of-the-art computers to manage loads, demands, power flows, and customer requirements.

Distributed generation

Distributed generation is a small-scale power generation that is usually connected to the distribution system (Rajalakshmi et al. 2016; Lede et al. 2017). Distributed generations are decentralised energy sources that can assist the main power grid in improving supply quality and reliability (Paital et al. 2018). The Electric Power Research Institute (EPRI) defines DG as generation from a few kilowatts up to 50MW (Kansal et al. 2019). CIGRE defines DG as the generation which is not centrally planned; it is not centrally dispatched at present; it is usually connected to the distribution networks; it is smaller than 50-100MW. The authors in (Ackermann et al. 2001) have given the most recent definition of DG as an electric power generation source connected directly to the distribution network or on the customer side of the meter.

Functional Relationship between DGs and capacitors

This relationship is based on the functional and operational similarities that DG and capacitors have on the distribution power system. DG and capacitors are both capable of providing the following system improvements:

1) Improving Voltage Profile
2) System Loss Reduction
3) Improving Power Factor.

Classes of distributed generation

Distributed Generators can be broken into three basic classes: induction, synchronous and asynchronous. Induction generators require external excitation (VARs) and startup much like a regular induction motor. They are less costly than synchronous machines and are typically less than 500 KVA.

Induction machines are most commonly used in wind power applications. Alternatively, synchronous generators require a DC excitation field and need to synchronize with the utility before connection. Synchronous machines are most commonly used with internal combustion machines, gas turbines, and small hydro dams. Finally, asynchronous generators are transistor switched systems such as inverters. Asynchronous generators are most commonly used with microturbines, photovoltaic, and fuel cells (Pujhari, 2001).

Types of distributed generation

Distributed generations offer real and reactive power support to distribution power system networks. The real and reactive power delivered to the system depends on the type of DG used (Acharya et al. 2006). On the basis of real and reactive power delivery, the DGs are classified into four categories:

1) DG1: only real power support to the system at unity power factor. For example, photovoltaic cell, solar systems, biogas, etc.
2) DG2: real and reactive power support to the system at 0.80 to 0.99 leading power factor. For examples wind, tidal, wave, geothermal etc.
3) DG3: only reactive power support for the system at 0.00 power factor. For example, synchronous condenser, a bank of inductors and bank of capacitors etc.
4) DG4: delivers reactive power to the system and absorb real power from the system at 0.80 to 0.99 lagging power factor. For example, doubly fed induction generators based wind etc.

Advantages of distributed generation (Acharya et al. 2006)

1) Flexibility - DG resources can be located at numerous locations within a utility's service area.
2) Improved Reliability by placing additional generation capacity closer to the load.
3) Security is improved by a local delivery point supply. This reduces the vulnerability to interrupted service from imported electricity supplies due to natural disasters, supplier deficiencies, interruptions, or acts of terrorism.
4) Reduced loading of T&D equipment by locating generating units on the low-voltage bus of existing distribution substations thereby extending the useful life of equipment and deferring planned substation upgrades.
5) Reduces the necessity to build new transmission and distribution lines or upgrade existing ones (Eroshenko et al. 2017)

Benefits of distributed generation

Basic tangible benefits that may be derived out of such sort of distributed or dispersed or decentralized generation are the following (Mukhopadhyay, 2009).

1) Easy and quick installation on account of prefabricated standardized components.
2) Lowering cost by avoiding long distance high voltage transmission.
3) Environment-friendly where renewable sources are used.
4) Running cost more or less constant over the period of time with the use of renewable sources.

Drivers of distributed generation

Distributed generation is capable of postponing, and certainly not of avoiding, the development of new transmission lines, as, at the minimum, the grid has to be available as backup supply (Driesen, 2006). The five major factors that contribute to the renewed interest in DG are energy efficiency or rational use of energy, deregulation or competition policy, diversification of energy sources, availability of modular generating plant, ease of finding locations for smaller generators, shorter construction time and lower capital costs for smaller plants, and proximity of the generation plant to heavy loads, which can reduce the transmission costs (Tautiva et al. 2008; Brown et al. 1997). These five factors can be grouped under two major driving forces, i.e. electricity market liberalization and environmental concerns.

Features of DG systems

Distributed generation systems can be described as small generation resources that are usually located near loads being served. Increasing the size of DG systems gives a vital solution to many concurrent power system problems because they are cost-effective, friendly to the environment, have high power quality and good reliability (Nebrir et al. 2006). Distributed generation systems have the following features:

1) Not centrally planned and mostly operated by independent power producers.
2) Not centrally dispatched (although the development of virtual power plants, where many decentralized DG units are operated as one single unit.
3) Smaller than 50 MW (although some sources consider certain systems up to 300 MW to be classed as DG).
4) Connected to the electricity distribution network which, although it may vary by country, generally refers to the part of the network that has an operating voltage of 240/400 V up to 66 kV.

Applications of DG systems (Gerwent, 2006)
1) Domestic (micro generation: electricity and heat)
2) Commercial (building related: electricity and heat)
3) Greenhouses (process related: electricity, heat and carbon dioxide for crop fertilization)
4) Industrial (process related: electricity and steam)
5) Grid power (only electricity to the grid).

Technologies of distributed generation

Distributed generation technologies are classified into renewable and non-renewable classes based on the type of fuels they use for their operations (Adefarati et al. 2001).

Non-renewable DG technologies

Non-renewable technologies use fossil-based fuels such as natural gas, coal, and petroleum to produce energy for different operations. Non-renewable resources are not sustainable and cannot be replaced by a natural means. Owing to these reasons, they will eventually run out of use because of the high rate of energy demand from the non-renewable energy resources is much faster than the rate of restoring them within the Earth. Examples of non-renewable technologies are reciprocating engines, gas turbines, micro-turbines, and steam turbines.

Renewable DG technologies

The DG technologies that fall under this category include geothermal power, biomass, solar power, photovoltaic (PV), small/mini/micro-hydro power and wind turbines. The output power of the renewable DG technologies can be dispatched to the grid based on the request of the utility grid operators or to operate as a stand-alone system to serve a particular load or an area. Recent studies by the World Energy Council have predicted that the global power output from renewable energy resources will increase from 23% as it was in 2010 to about 34% in 2030 (World Energy Council, 2013).

Comparison between solar photovoltaic and wind energy as DG

In recent years, technological innovations and a changing economic and regulatory environment have resulted in a renewed interest for DG units. Different technologies are used for DG sources such as photovoltaic cells, wind generation (Blaabjerg et al. 2017), combustion engines, fuel cells and other types of generation from the resources that are available in the geographical area (Barker, 2000).

Both wind and solar generation can be beneficial to the electricity network as they have the ability to provide clean energy with zero fuel costs (Shivarudraswamy et al. 2012).

Solar generation is relatively simple to predict as it mainly depends upon solar irradiance, temperature, and shading. Whereas wind generation is more complex as it depends upon the forever changing wind speed which affects the power output exponentially. This leads to the trade-off between predictability and generation capability. Solar is more predictable but is less efficient opposed to wind generation being harder to predict but offers a much higher generation efficiency. The higher efficiency of wind turbines and there significantly cheaper production costs have made them very attractive to investors seeking to invest in renewable generation technology.

Impact of distributed generation on the distribution network

Based on the location, the size of the DGs also depends on the load profile which can bring both positive and negative impacts (Lopes et al. 2006; Patil et al. 2017).

The connection of DG, if operated at leading power factor mode, may increase the voltage by adding reactive power to the network. The direction and magnitude of real and reactive power might alter based on DG location and size (El-Ela et al. 2010; Borges et al. 2006). Due to uncoordinated operations for regulation, more challenges may arise such as power loss increment and a number of switching Distribution systems are planned and designed considering transmission line parameters, loads and generation capability. When DGs are introduced in the distribution system without any action taken, it might have a significant impact on the system power losses. Based on the location, the size of the DGs also depends on the load profile which can bring both positive and negative impacts (Lopes et al. 2006).

Technical challenges facing DG

Distributed generation systems are often smaller systems that are locally integrated into the low voltage distribution system which conflicts with the existing power network design paradigm. Adding DG to the existing electric power distribution system can lead to a reduction of protection reliability (Matos et al. 2017), system stability and quality of the power to the customers (Pujhari, 2001).

In addition, there are several negative impacts (Davison et al. 2017) such as frequency deviation, voltage deviation and harmonics on network (Kumpulainen et al. 2004; Bari et al. 2016). The increase of power losses is another effect that may occur (Tautiva et al. 2008; Reddy et al. 2012). Thus careful considerations need to be taken when sizing and locating DGs in distribution systems.

The following are some of the technical challenges created by distributed generation in the power system (Kumpulainen et al. 2004):

1) Voltage Regulation, losses, and flicker
2) Distributed generation Shaft Over-Torque During Faults
3) Harmonic Control and Harmonic Injection
4) Increased Short Circuit Levels
5) Grounding and Transformer Interface

Challenges to the protection of distribution networks due to DG

Widespread distributed generation has been found incompatible with conventional distribution system protection approaches (Udgave et al. 2015) such that distribution protection practices should be put in place in order to accommodate DG integration (Amrit et al. 2015). Some of the most commonly mentioned challenges are the following (Conley, 2009):

1) Unintentional islanding with concerns about reliability, safety, and power quality. Especially when automatic re-closing is applied, even momentary islanding can be very detrimental. Anti-islanding protection is regarded as one of the most challenging questions to be solved in the field of distributed generation.
2) The operation of DG units can cause failure to the operation of protection. Fault current produced by DG units may reduce the current seen by feeder relay.
3) Distributed generation may cause unwanted operation of protection. DG units can cause tripping of healthy feeders in adjacent feeder faults.
4) Distributed generation may require upgrading of primary substation busbar protection. In busbar fault, it is no longer adequate to trip only the infeed from the HV/MV transformer because there are fault current sources also in the feeders. The existence of DG may also require changes in protection interlockings.
5) Nuisance tripping of production units.

Voltage control

The active power flow on distribution networks has a significant effect on the voltage levels due to the high resistive levels of distribution lines compared to transmission lines (Kimberley, 2014). In low penetrated networks, DG units do not involve in voltage control activities of the Point of Common Coupling (PCC). Instead, it operates in power factor correction mode, where the power factor keeps closer to unity. Most of PV units and Wind generators work in this way. Since most of the Renewable sources are connected to low/medium voltage lines, voltage control of the distribution network is the real issue to overcome by network operators when there is an integration of renewable sources (Matlokotsi et al. 2016). The amount of DG units connected to a particular distribution network is limited by the voltage control margins of that distribution network. Automatic tap control transformers, SVC and STATCOM are used by operators to control the network voltage.

Power and frequency control

To achieve frequency control through renewable sources, several methods are possible. The following list shows some important methods for achieving power flow control and frequency control.

1) If a renewable energy source is a dispatchable source such as Solid Oxide Fuel Cell (SOFC), bio-energy based microturbine, Hydro it can participate in power and frequency control activities.
2) Non-dispatchable renewable sources (PV, wind) can be converted as dispatchable with energy storage systems. Batteries, supercapacitors or pump hydro methods can be used as an energy storage medium.
3) Change the power delivery point of intermittent renewables from its maximum operating point and run them with some reserve power margin. In this method renewables (PV, wind) will not capture maximum available power from sources and which leads to economic challenges of the operations. With these methods, renewables can also participate in frequency control same as conventional synchronous generators.
4) Demand side management where non-critical loads schedules can be a shift to a time period where the grid has excess power (Senanayaka, 2014).

Effects of DG penetration

Adding DG into a simple distribution network (DN) drastically changes the DN environment and variables. One of the advantages is the reduction of demand on the main feeder and its tie lines, resulting in the delay or postponement of equipment upgrades due to load growth. Evenly dispersed generation also has the ability to support the local voltage, making the voltage profile more constant for DN that suffered poor voltage levels before installation of DG during peak loading scenarios (Ilse et al. 2014). Richardson et al. 2009) were able to show that under normal operating conditions, the possibility of 100% DG integration resulted in voltages within operating limits. However, there are a large number of effects that are viewed as negative for the design, voltage profile and protection of the DN. These negative effects limit the amount of generation that can be adopted on a DN.

The DG has the effect of improving voltages and slightly destabilizes the protection equipment by changing the demand values and short circuit ratings originally used in the protection study. The losses in the DN are also reduced, benefiting the Distribution Network Operators (DNO) costs (Quezada et al. 2006). If the generation is induction type, capacitor correction is recommended at the Point of Common Coupling (PCC) to keep power factors near unity.

Distributed generation opportunities and challenges

Opportunities

Given the potential and probable application of interconnecting the dispersed DG "stand-by generating systems", generating capabilities provide several benefits to both utility and consumers (Zobaa et al. 2006).

The consumer will have consumption choices; they can reduce their energy expenditures by incorporating DGs that are powered by cheaper fuel sources, for example, the use of methane gas fueled turbine-generating units. Methane gas can be produced in a nearby landfill. Heat can also be produced through the burning of waste in incinerators; otherwise, it will be produced using electricity. Using local or nearby fuel sources that could be generated from large amounts of municipal waste that otherwise need vast landfill sites adds to cities' energy supply chain.

As for the utility, it can use the DG power to enforce its distribution network voltage stability, as well as to increase its peaking capacity without suffering financial costs.

By allowing consumers' own DG units to provide electricity during high electricity rate and short-term supply interruptions, continuous productivity is ensured and the reliability and power quality of the consumed electricity is increased. DG owners or operators could also receive a new source of revenue from electricity sales to the hosting electricity provider.

Challenges

Since the introduction of DG provides an unwanted source for re-distribution of both load and fault current, as well as a possible source of overvoltage and islanded operation (Nigim et al. 2003), the investigated requirements are looking at issues such as performance, operation, testing, safety and maintenance of the interconnection. The current engineering practice for DG/Utility interconnected systems is to revert the utility systems to its original configuration (radial or meshed distribution system) with all interconnected DG units de-energized whenever an unexpected disturbance occurs in the system.

Since most distribution systems comprise radial feeders, this practice leads to the discontinuation of the supply for all the downstream customers. Thus, the system reliability stays at the same level as it was before integrating the DG with the system (Barker, 2000; Dugan et al. 2009; Kojovic et al. 2001). At the same time, there exist in the system some unsupplied loads and unutilized DG capacity. If interconnected DGs are permitted to supply loads during utility outages, the system reliability will be much better and the customers will not experience any discontinuity of their supply. This goal can be achieved by simply coordinating intention islanding of DG units (Friedman, 2002).

Conclusions

In this paper, literature review of distributed generation applied in the power system has been explained in details. A brief overview and technical know-how of these power generation alternatives are given. Outline of precautions to be taken during stages of planning, sizing and placement are presented along with challenges utilities face in the operation. This paper serves as a source of information for researchers interested to do research on distributed generation and related study areas.

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