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REVIEW OF DISTRIBUTED GENERATION, MODELING AND ITS IMPACT ON POWER SYSTEM STABILITY

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ABSTRACT
This paper reports on the review of the emerging distributed generation (DG) and its impact on the stability of power system. It discusses various aspects of DG such as technologies, benefits, challenges, environmental impact and impact on overall power system stability. It also reports on hybrid power system as a viable means of maximizing the use of some primary energy sources that are non-dispatchable but abundant. Moreover, the current issues of DG in relation to system stability are also presented.

KEY WORDS
Distributed generation, stability, hybrid power system, microgrid.

1. Introduction

The interest in distributed generation (DG) has considerably increased due to market deregulation and growing concern about global warming and climate change. The industry restructuring process and the desire to reduce green house gas emission is driving the power and energy sector in general away from the traditional vertical integration and cost-based regulation towards increased exposure to market forces. Under the DG paradigm, small generators, also known as distributed generators, are now being connected close to consumers at the distribution level. Without DG, the network is a passive one that supplies power only in one direction, i.e. from utility generation to loads. When DG is connected to the network it becomes an active network with possibility of bi-directional power flow in radial distribution feeders. DG enhances consumers' satisfaction with higher energy efficiency, short construction lead time, modular installation and low capital expense [1]. This paper reviews the emerging DG concept and its impact on overall power system stability. Different surveys indicate that DG could create disturbances in the operation of active distribution networks. Several studies are undertaken in UK and Europe by the Department of Trade and Industry (DTI), Technical Steering Group (TSG), Distributed Generation Coordinating Group (DGCG), CICRE and others for investigating the technical, commercial and regulatory benefits and risks related to the deployment and integration of DG units[2].

Literature review confirms concern over several technical issues related to rising DG penetration in the system which are yet to be solved. Much benefit could be lost if the DG unit is not properly integrated or technical and regulatory issues are not properly addressed. Technical studies clearly indicate the need to review the established grid codes and guidelines in order to accommodate more DG in the system [2]. IEEE and CIGRE are trying to bring out a unified connection rule so that the 'fit and forget' approach and disconnection during fault could be avoided. This policy is consistent with historic passive distribution network operation. New network structure emerged with various operators at each level known as Distribution Network Operator (DNO) and Transmission System Operator (TSO). However, with the present approach DG will not be able to provide flexibility and controllability of conventional plant and provide network support [3]. Thus it is possible to operate DG in a safe and satisfactory manner provided the identified criteria are met. There are capital and revenue cost implications to meet the necessary criteria for both the DG units (e.g., extra cost of integrating DG units through power electronic converters). The cost varies significantly for different sites of application and the size and type of DG unit [1]. High installation cost of some DG technologies could actually discourage its participation in DG markets. The nature of the load in an open market is stochastic as ownership of DG could be utility or consumers [4]. The network operator is not only faced with this complex nature but equally have responsibility to ensure system stability. However several benefits of DG are identified for customers, suppliers, DNO, TSO, independent power producers (IPPs), project developers and DG manufacturers. These include ancillary services and reducing financial penalties the DNOs face for customer interruptions and network unavailability [4-6]. Fuel shortages, reduction of environmental pollutants, liberalization of electricity market, diversification of energy sources to enhance energy security are identified as the various drivers of DG [7]. The area that henceforth needs to be addressed critically is the instability arising from the connection of DG into the distribution network. From the technical point of view, the connection of DG unit to distribution networks or grid (i.e grid-connection of DG) is a challenging task. The basic reason for this is that distribution networks are typically not planned for accommodating any generation e.g., the traditional over current protection scheme of a medium voltage (MV) network relies on fault current being fed from one direction only [8]. Hence the control mechanism provided by the conventional large scale power plant could not be used for the DG at the distribution level. However, if DGs are not fully integrated, they would not be able to substitute for network assets and to control the dynamics of power system network. DNOs are further exposed to challenges of maximizing access for the connection of DG generation units and also maintaining the established levels of power quality, availability and reliability of the distribution network at a reasonable cost. Instability arising as a result of fault, large penetration of DG, difference in generation technologies and network strength at the point of connection pose more concern. The impact of DG in performance of distribution and transmission networks thus clearly depends on the type of DG technology, density and degree of penetration [1,9].

It is probable that guidelines and regulations like G59/1, G75 and Engineering Technical Report 113/1 will be updated in near future in the light of the new code that are being developed to ensure grid stability during and following a major fault in the transmission network [1]. This will ensure a common approach for the benefit of overall network stability and resilience.

2 Definition of DG Brief Summary

The definitions for DG used in the literatures however are not consistent. In the literatures, a large number of definitions are used in relation to DG. For example, embedded generation, dispersed generation and decentralized generation are used commonly by different countries to represent DG. In all of these, the central idea is that DGs are not centrally dispatched. Different groups like IEEE, CIGRE, IEA (International Energy Agency), etc. define DG differently but the generally mentioned criteria among them is,

- Not centrally planned and dispatched.
- Usually connected to the distribution network.

It is on this note that Ackermann's definition is used as the base case.

Ackermann defines distributed generation as an electric power generation unit connected directly to the distribution network or connected to the network on the consumer side of the meter[10]. A further narrowing of this definition such as being dispatchable or not might be necessary depending on the research question that are investigated [11].

- However, Momoh defines DG as typically small electric generation plants using either combustion based technologies, such as reciprocating engines and turbines, or non-combustion based technologies such as fuel cells, located on or near end–user and are characterized as renewable or co-generation non-dispatched sources. They are also called embedded system or dispatched system [12]. This definition also follows the factors identified in reference [10] that must be contained in DG definition. For example, the followings are clear from the definition[12]:
- Purpose: to deliver active power to end–user
- Location: on or near end user.
- Technology: it indicates technology as reciprocating engines and turbines, or non-combustion based technologies such as fuel cells.

Other factors are not really essential and cannot be used to define DG. This latter definition agrees with the detailed report presented in [10] and [11].

3 Distributed Generation Technologies

Some DGs are already well-developed and are in use over several decades. Others are in different stages of development and commercialization [13]. They generally possess characteristic that allow easy integration to the grid. DGs are basically described on the basis of their capability for grid connection, capability to ensure grid stability and easy implementation. In addition to grid connection capability, DGs are also classified based on primary energy sources, though the latter is used for a general description [9]. Challenges currently faced by the network operators are optimal integration of the increasing number of small generating units into the grid. As reported in some works [11,14], combined heat and power (CHP) technologies (e.g., diesel engines, natural gas engines, gas turbines, micro turbines, fuel cells, stirling engines, etc.) are promising DG technologies in terms of their output and start–up time. It is therefore indicated by these papers that full knowledge of these technologies could contribute to improve system stability. Table 1.1 lists different DG technologies and indicates their potential benefits [11].

TABLE 1.1 Distributed generation technologies and their potential benefits

	Stand by	Peak Shaving	Reliability	Power Quality	Avoiding Grid Expansion	Grid Support (Ancillary Services)	Co-generation	Green power	Cheap fuel Opportunity
RE	YES	YES	YES,IF DISPATCHABLE		YES,IF DISPATCHABLE	YES,IF DISPATCHABLE	YES	NO-YES[a]	NO-YES[a]
GT	YES	YES	YES,IF DISPATCHABLE		YES,IF DISPATCHABLE	YES,IF DISPATCHABLE	YES	NO-YES[a]	NO-YES[a]
MT	YES	YES	YES,IF DISPATCHABLE		YES,IF DISPATCHABLE	YES,IF DISPATCHABLE	YES	NO-YES[a]	NO-YES[a]
FC	YES	YES	YES,IF DISPATCHABLE		YES,IF DISPATCHABLE	YES,IF DISPATCHABLE	YES	NO-YES[b]	No
PV	NO	NO	NO		DIFFICULT	DIFFICULT	NO	Yes	Yes
WT	NO	NO	NO	NO	DIFFICULT	DIFFICULT	NO	Yes	Yes
Other Renewa-bles	NO	NO	NO(EXCEPT HYDRO)	NO	DIFFICULT	DIFFICULT	NO(EXCEPT BIOMAS AS FUEL)	yes	Yes

[Courtsey : G.Pepermans et al./energy policy 33(2005)]

Note:
RE: Reciprocating engines; **GT:** Gas turbines; **MT**: Micro Turbines; **FC:** Fuel cell; **PV**; Photovoltaic; **WT:** Wind
YES: Technology contributes to; **NO:** Technology does not contribute to; **Difficult**: Require significant additional technologies, for example extra energy storage
[a]Green power is possible when biogas or biodiesel is used
[b]Green power is possible when hydrogen is produced via electrolysis, using wind or solar

4 Challenges of DGs

It is generally identified from literatures [11,15] that when DG is fully integrated, it can provide uninterrupted quality power, premium power, peaking and ancillary services like voltage support. DG continues to face many challenges which have over time opened up new research areas. The most challenging research issues as discussed in literatures [7,13]are:

- Impact of DG connection point in a distribution feeder on the technical operation and control of the distribution system;
- Maintaining ancillary services in the new market environment;
- Keeping an acceptable voltage level for all consumers of the power system;
- Maintaining power balance of the system;
- Voltage regulation in addition to tap-changing transformer;

Uniform interconnection standards for addressing safety, power quality and reliability are also reported in [12].
Networks are often subjected to voltage rise. This is because of the bi-directional flow of power, posing a limitation to the DG capacity that can be connected to rural distribution network. Stability problem is traced to the high level of DG penetration to a distribution network. The heavier the load on the lines, the weaker the connections between the generators and the loads and the larger are the oscillations of the centralized generators. Therefore to determine the DG penetration limit for a specific case, detailed analysis (transient stability analysis as regard the ability of central generator to supply reactive power or inertia) must be done on the network. Till now, there is no established rule or guideline on the amount of DG that should be connected to a network.

5 Dynamic Impact of Distributed Generation on Distribution Network

It is understood from various works [7,9] that the implementation of DG influences both steady state and dynamic performance of a power system. Dynamics is often used in power system literatures to signify that every component of the system experiences motion. Consensus has been reached already on the definition of stability as indicated by most papers [8,17,18]. The result obtained from various level of transmission systems agree with the current attention diverted to research stability issues by researchers both in industry and academia. Many blackouts and shut downs are recorded in recent past. However power system stability is the ability of electric power system, for a given operating condition, to regain a state of operation equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remain intact [18]. A lot of work has been centered on transient, frequency and voltage stability as well as small signal stability. Literature [17] analyses and reports on the probable factors causing stability problems, such as gradual change of load, loss of generation, lightning strikes, etc. Recent development in power electronic technology that includes power converters, pulse width modulation (PWM) techniques, control algorithms and electronic control unit is definitely helpful for minimizing the harmful impacts of DG penetration in grids [19]. Effect of DG on the system could go beyond distribution level as penetration level increases [9]. In that case DG would also have significant impact on the MV and even HV distribution networks. Most papers conclude as follows:

- The transient stability analysis shows that the maximum power-angle deviation between the generators decreases with increase of the penetration level of the DG units[20].
- DG leads to load reductions which in turn reduces the power flows in the transmission network, eventually improving its transient stability [9];

Common indicator to measure these effects are reported in papers [9,17]. Critical clearing angle (CCA) and critical clearing time are often used as power system stability indicators but recent research makes the use of oscillation duration, maximum rotor speed as indicators [9].

The fault criteria used to indicate this impact are connection strength, fault impedance location and duration, protective scheme, DG technologies, type of power electronics interface, etc. A diagrammatic classification of DG for simple stability studies is made in paper [9]. They are classified on the basis of environmental impact (renewable), output characteristic (dispatchable and non disptchable) and grid connection characteristic (direct and indirect grid connection). Classification based on output and grid connection characteristics focus on the interaction between the DG and the grid is shown in Fig. 1.1.

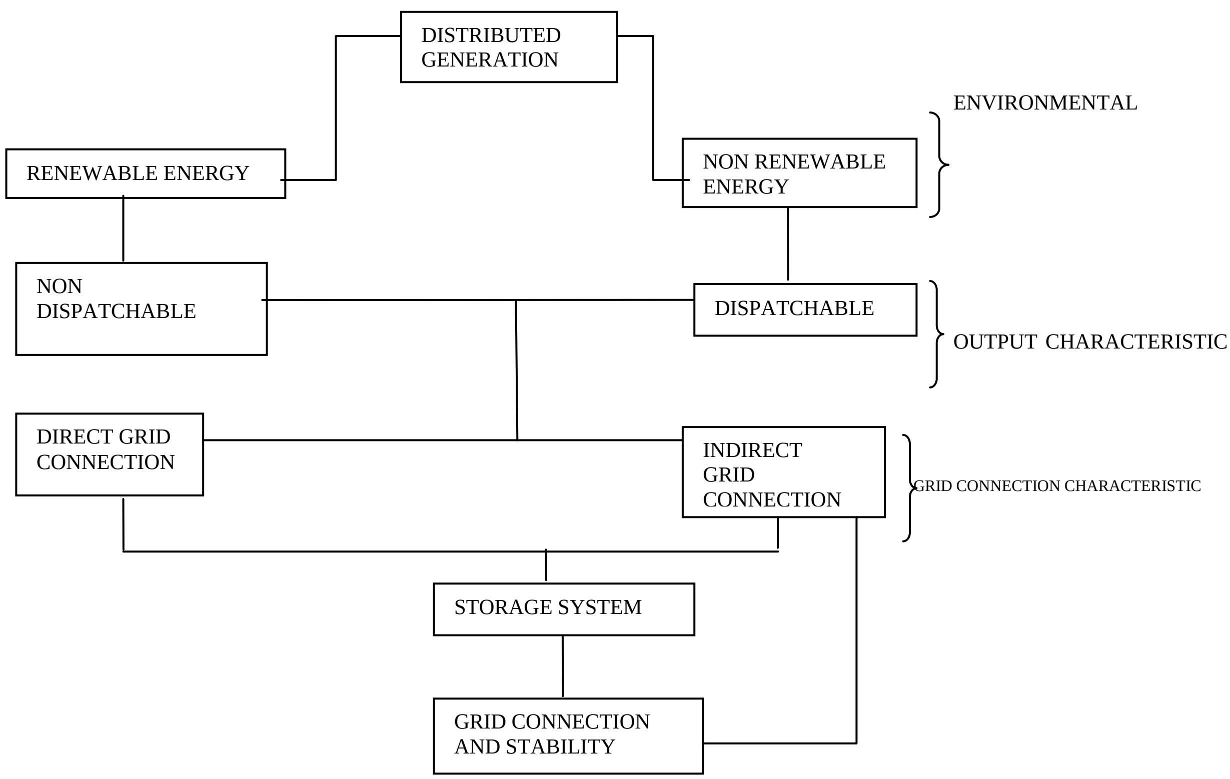

Fig. 1.1 Classification of Distributed generation

6 Modeling of Distrubted Generation

DG may operated in two modes: operation in parallel with the grid (grid-connected) or operation independent of the grid (islanded or stand-alone). The former is typically referred as emergency and standby power. In grid-connected mode, protective relaying is required to protect the DG unit and facility of the power system from adverse effects introduced by the grid and to protect the grid from adverse effects introduced by the DG units. Therefore an accurate DG modeling for dynamic behavior studies is a key issue to get an adequate idea of the impact the DG may have on the network and vice versa, specially under fault conditions and disturbances. Many papers present the issues of modeling of DG unit for power system stability on technology basis. Directly connected DGs (e.g., fixed speed wind turbines) are gradually fading away in the market because of their uncontrollable reactive power consumption, mechanical stress and limited power quality control and the fluctuation in the wind speed which gets directly transferred to the train torque fluctuation [21].

The main advantages of indirectly connected DGs (e.g., variable speed wind turbines) are better power quality and reduced mechanical stress on the wind turbine. An accurate modeling of these systems should include not only the turbine and generator model but also a detailed model of the power electronic converter. Some converters which are commercially available in the market include: 1) back-to-back converter, 2) multilevel converter, 3) tandem converter, 4) matrix converter, 5) resonant converter, etc. Out of these, the back-to back converter consisting of two conventional pulse-width modulated (PMW) VSC converter is often used in wind energy conversion systems.

6.1 Modeling of distribution utility

Distributed utility is a concept that anticipates an increased use of distributed resources to enhance the efficiency of the power system. It comprises modeling of DGs and other ancillary parts that that may alter system stability. DG modeled as generator with real and reactive power injection falls into the following categories as reported in [12] : 1) synchronous condensers for increasing the energy margin and providing stabilization via frequency and voltage control, 2) induction generators used to maintain constant voltage even if its frequency, voltage and phase may deviate within acceptable tolerances, 3) UPS with grid inter-tie to serve as battery backup to a fraction or all of the consumer's loads with optional grid inter-tie is power quality and synchronization conditions are passed by utility. Type1 and type 2(DG) are used in sub-transmission level (MW) while Type 3(DG) is used in distribution level (kW). Most papers determine the choice of modeling by the following considerations:

1) Type of generator
2) Output of the generator
3) Mode of operation (grid-connected or islanded)
4) Type of stability to examine (transient, voltage or frequency)
5) Type of connection
6) Time and frequency of various dynamic phenomena in power system.
7) Aggregation of DG units according to their types
8) Application need

To avoid too much modeling error, normally a model of the power system and its components that is tailored to the phenomenon under study is used [21]. Such a model must be based on frequency consideration. Two methods of simulation are identified in literature [21] such as fundamental frequency simulation or electromechanical transient simulation and electromagnetic simulation. Major differences are in frequency and time of various dynamic phenomena in power system.

In electromechanical simulation, the network transient is assumed to have a short time constant and hence is neglected. The network is represented with impedance matrix considering only fundamental voltage and current and higher harmonics are neglected. The assumption also implies that at the terminals of generator and loads only the fundamental frequency component should be present, in order to have a consistent representation of the whole system. Time response of (10s-100ms), frequency (0.1Hz-10Hz) are used.

In electromagnetic transient simulation, network is represented by differential equations and the time step is in order of microseconds or smaller. In this simulation, shorter times are incorporated so that high frequency phenomenon can be studied. In case of load following and dispatch, where the emphasis lies on the load pattern and the characteristic of the primary energy conversion where the order of time is in order of several second or minutes [21].

It is discussed in some works [22,23] that large megawatt of power could be anticipated for some grids (e.g Danish wind farms). It therefore suggested with proven analysis that an equivalent model can be produced from the aggregate model. The sum of the output power and MVA rating of each generating equipment is used to produce the equivalent modeling for the system under the assumption of same operation points. The references conclude that simplification of aggregate modeling of DG (e.g., wind and solar) produce better way of analyzing the dynamic behavior of the system. The result was validated as well by [24]. Again generators with no or very little inertia may become pose stability problems [7]. Power system inertia influences power system stability. So when integration of more and more converter connected low-inertia DGs is combined with taking out of high-inertia centralized generators, the system will be more vulnerable to disturbances. Examples are solar, storage system, fuel cell etc.

7 Stable System

In real sense, there is no single stable state for a power system. It solely depends on the operating condition and faults on the network. That is why the power system is equipped with different controllers at each level to ensure stability. Various literatures analyze and itemize the enabling factors for achieving a stable system as listed below:

- DG can improve stability if suitable types and appropriate locations are selected [20].
- Dispersed DGs over several connection points instead of concentrating them in a single point gives a better stability [9].

- Hybrid power systems (HPS) are good ways to harness available sources of electricity which optimize utilization of primary energy sources [25].

Small scale HPSs for stand alone application already exist. The current challenge is fully integrating the HPSs into grid and the possibility of producing power from both sources simultaneously.

8 Microgrids

The novel idea of microgrid [26] has also encouraged the deployment of DGs by highlighting the potential benefits that could be obtained by integrating DGs through intelligent or smart controllers and SCADA systems. The concept is new and it is still at its budding stage, though thoroughly researched in different countries. Microgrid is defined as low voltage network with DG sources together with local storage devices and controllable loads (e.g., water heaters and air conditioning [25,26]. Microgrid is composed of locally placed sources, loads and energy storage required to maintain the local balance between available generation and power demand. The key feature is its ability, during grid disturbance, to isolate itself from the utility seamlessly with little or no disruption to the loads within the microgrid. Most papers highlight that the benefits derived from microgrid would include network support and ancillary services, easy storage mechanism, improving power system quality and stability, easy energy management, promote real time control, operation and planning, etc. [16, 26].

9 Future Focus of DG Applications

With further development and deployment of DG across the globe, a proportion of the electricity generated by large convectional plants will be displaced by renewable and other forms of DG. Storage facilities are needed when the output of these renewable energies sources are fluctuating. Such generators include solar and wind power systems. Literatures [9,14] identify that a new horizontal network structure is likely to replace the conventional vertically integrated structure of power system. Greater attention will be diverted towards this system as to fully maintain it in a challenging market environment. Besides, distribution companies will deal with customers who are more aware of the possibilities offered by market and their online services. These include competitive tariffs for local generation, supporting scheme for renewable energies, cost-effective energy-saving programs, demand–side management, communication and billing services, etc. [16]. IPPs now ensure that customers are being paid for exporting power into the grid. Often billing system under new electricity deregulation is a complex issue. However the new system will gradually reduce the dependency on oil and other depletable resources like coal, gas etc. Issues related to control are treated through microgrid concept [26] that is coming up because of the introduction of DGs. Microgrids possess similar characteristic to the large conventional grid system with the difference that microgrids function through small generators. However, new methods of network planning (such as short–term load forecasting, assessment of renewable resources, drawing solar and wind maps, prediction of solar and wind energy), operation (optimal power flow, unit commitment, generation scheduling, state estimation, static and dynamic security assessment, dynamic contingency analysis, fault detection, substation maintenance, condition monitoring, etc.), analysis (dynamic stability assessment, generation voltage and speed control system design, etc.) are going to be the main research focus. As the generation technologies become more matured and better understood, the power system may evolve into what can be referred to as a distributed utility where DG is only one component of the distributed utility concept [1].

10 Conclusion

The paper presents a summary of DG concept, its impact on overall system stability and system study and modeling and simulation requirements. The paper highlights different DG technologies and relevant benefits, challenges and stability issues. It is evident that increasing DG penetration in the distribution network requires new approach in system operation, extensive modeling and simulation and system studies for a better understanding of the generation technologies and their impacts on the grid and modification in grid codes and guidelines in order to maximize the benefits of DG in enhancing overall power system stability. The stochastic behavior of solar and wind energy needs a thorough analysis to enhance the use of these abundant natural resources. The combination of wind and solar power generation is complementary and could considerably improve stability. There is an equal need to integrate them to transmission line with thorough investigation on its stability. Further research is therefore essential in these areas. Future course of research of the authors will be modeling and simulation of the proposed hybrid power system, dynamic analysis and investigation of its impacts on overall power system stability.

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