Department of Mechanical and Aerospace Engineering

Distributed Generation
And
It's Impact on The Grid

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Signed: Sibildas Mulayaniparambil Date:20/08/2018

Abstract

The recent improvements in the renewable energy-related technologies, as well as the growing awareness about the global warming effects, drive to a rapid development of the distributed energy sources. Some countries had already adopted to establish the renewable energy on their grid, and many are on the progressing stage to expand their renewable share on the grid to lessen the pollutions from the fossil-based electricity production for accomplishing the set targets of diminishing the greenhouse gas emissions. However, despite the positive impacts, the rapid growth of renewable penetration can make adverse effects on the grid. Such a wide spread of distributed renewable generation demands the current grid infrastructure to be transformed and renovated to adopt high penetration levels of distributed generation. As many are still unaware about the downside of distributed generation penetration, this thesis strives to study some of the possible consequences of such generation and tested its influence on the electrical parameters based on the UK legislative requirements. To study the impact of distributed generation a prototype network model provided by the IEEE has chosen to integrate the distributed generation plants. The distributed plants have penetrated to the 33kV distribution voltage level, and numerous studies are conducted using the ETAP software. The methodology adopted is the scenario-based approach, and the distributed production plants employed are the most widely available renewables, wind, and PV plants. Various scenarios are assigned based on the penetration level of distributed generation, and the influences on the different electrical parameters compared with the help of simulations from different tests. The parameters examined to investigate the impacts are the influence on voltage, frequency, short-circuit fault level and harmonics due to the distributed penetration. The achieved results show that any penetration below 30% is tolerable based on the UK standards while the higher penetration resulted in substantial variations from the approved ranges on the electrical parameters. Therefore, any penetration beyond the 30% limit necessitates further attention and modification of the existing grid infrastructure before the DG integration.

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List of Abbreviations

AC	Alternating Current
CB	Circuit Breaker
CHP	Combined Heat and Power
DC	Direct Current
DECC	Department of Energy and Climate change
DFIG	Doubly Fed Asynchronous Generators
DG	Distributed Generation
ENA	Energy Networks Association
ETAP	Electrical Transient and Analysis Program
GWEC	Global Wind Energy Council
HV	High Voltage
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-Gate Bipolar transistor
IRENA	International Renewable Energy Agency
LG	Line to Ground
LL	Line-to-Line
LLG	Line-to-Line to Ground
LV	Low Voltage
LTC	Load Tap Changer
MGT	Micro Gas Turbine
MPPT	Maximum Power Point Tracking

MV	Medium Voltage
MVAR	Mega Volt Amps (Reactive)
MW	Megawatt
PCC	Point of Common Coupling
PV	Photovoltaic
PWM	Pulse Width Modulation
SCR	Silicon Controlled Rectifier
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
W	Watt
Wp	Nominal Watt Peak Capacity
WTG	Wind Turbine Generator

1. Introduction

1.1. Background

The increased awareness of about the greenhouse emission and its adverse effect like global warming lead many countries to think about an alternative approach to generate electricity apart from the carbon-emitting fossil fuel-based technologies. It drives to the development of the renewable-based electricity generation. Currently, in worldwide, the renewable sector market is undergoing a rapid growth. The latest developments in the renewable generation technologies, as well as the improvements in the method or techniques used for the electricity generation from the natural resources, are the main reasons. The fast growth of the renewables as well as the emergence of the cogeneration systems, and new energy storage technologies can significantly reduce the carbon emissions, thereby contributing to the commitment of the most developed countries to meet their greenhouse gas emissions reduction targets (as per the Kyoto protocol). Because of the comprehensive research and introduction of new techniques and technologies, the electricity generation from the renewables is becoming cheaper. Hence, the use of renewable as an alternative supply is also increasing in the developing countries like India. The implementation of various renewable energy mixes such as wind, photovoltaics, and hydro are becoming a common trend across the worldwide. In general, any such decentralized generation that penetrates the distribution network is called distributed generation (DG). In the EU, it is expecting that the renewable energy generation mix will reach around 30% in 2030 as per the set targets (European Commission, 2016), and in the UK, aiming for 15% of energy demand from the renewable sources by 2020 (DECC, 2011). Therefore, the growth of the electricity generation from the renewables or distributed sources is expected to continue. However, apart from the economic and energy markets capabilities, this rapid growth raises a significant question that whether the technologies are technically mature and available to support this boost?

Electrical power systems mainly constitute of generation, transmission, and distribution systems. The renewable systems are not always centralized and unable to generate bulk amount of electricity; hence, its shared over the network and such generations are becoming enviable. However, the traditional network design was not intended to include such generation on large scale. Thus, the conventional network main characteristic of central generation from big plants to the distribution network and then to the customers are no longer a single method of flow of electricity. Therefore, the large decentralised electricity generation might create problems with the electrical system. For many countries, the distributed generation has proven to be a good solution for the various environmental, technical, political, and economic obstacles. For instance, it increases the reliability of the overall system, covers the peak load by consuming less power from the utility, and hence, decreases the electricity bill and covers the step increase of power demand. However, it is required to perform an intensive technical analysis to determine the impacts on large-scale installations. The knowledge about the higher penetration level makes the policymakers to limit the generation under the permitted limit. Any integration beyond this limit requires the current infrastructure to be modified to adapt to the high distributed penetration. Otherwise, the unlimited growth of distributed generation may lead to a catastrophic failure of the electrical power system.

Therefore, in this thesis, various studies are handled to understand and determine the impact of DG penetration into the distribution network. Also, tried to determine the possible penetration level into the network. As PV and wind are the most commonly available and widely used distributed generation technologies, the impacts from these investigated in this thesis. It is always advisable for any electrical network that the voltage, frequency, and current should not increase beyond a limit for the general safety, and to avoid the damage of different types of equipment connected with the network. For instance, the protection system is principally designed based on the maximum fault level current, and hence, any increase above the maximum limit would harm the system. As the electricity fed from the distribution network to the customers, the changes in the electrical parameters of the distribution network might create problems at the consumer ends as well. Hence, the impacts of PV and wind distributed generation on the distribution voltage, current and frequency levels are studied in this thesis. Also, the introduction of power electronics devices within the PV and wind electrical systems that were not present in the traditional system is expected to create some additional problems related to the power quality. Therefore, the power quality problems, mainly the harmonics created due to the introduction of DG systems are also studied.

At first, the thesis was intended to conduct the research based on the existing UK network model. However, the opportunity to access the original data and the permitted timeframe were limited. Therefore, decided to use the most viable accessible data for approved distribution system models. Thus, it guides to the IEEE test feeder distribution model; the one which is widely used by different researchers. Then, the analysis outcomes from the test model are evaluated based on the UK standards.

1.2. Problem statements

The rapid growth of renewable penetration into the distribution network might create an unfavourable effect on the power system network. Therefore, in all countries, where the distributed renewable generation expands widely, it is necessary to think about the problems related with the distributed penetration and the maximum penetration level that would not create problem to the electrical power network system. As in the other developed countries, for the UK, the wind and PV systems are expanding widely. Hence, it is desirable to have an understanding about the impacts due to the distributed systems into the electrical network. Therefore, in this thesis, based on the IEEE test feeder distribution network, the effects of distributed renewable penetration into the grid and the possible limits of penetration level is studied.

1.3. Overall Aims

The overall aim of this thesis is to study about the distributed generation (DG) and its impacts on the grid.

The main objectives are:

- To study the distributed generation (DG).
- To examine the impact on the grid voltage because of the DG penetration.
- To investigate the influence of the short-circuit fault current levels due to the DG penetration.
- To examine the frequency impacts at the grid because of the DG penetration.
- To review the harmonic effect on the grid voltage due to the DG penetration.

1.4. Methodology

The methodology adopted in this thesis is the simulation and analysis of different scenarios. The IEEE 30 bus test feeder network is selected to model and to study the impacts of the distributed generation penetration into the grid. The most appropriate method was to model the real network. However, by considering the available time frame, a representative prototype network is used for this thesis. The IEEE 30 bus distribution network feeder has the voltage levels like the UK distribution voltage levels, and the network parameters used in the test feeder based on the relevant international standards like IEEE standards. Therefore, it can consider as a prototype of the actual electrical network system. Thus, the IEEE test feeder is modelled in the software and studied the impact due to the DG integration into the network. The computer software used in this thesis for simulation is one of the widely used power system analysis software, ETAP ("Electrical Transient and Analysis Program"). ETAP provides the most comprehensive renewable energy models, and, performs various complex power system related calculations such as load flow analysis, short circuit fault level, transient stability, and harmonic analysis as per the ANSI or IEC standards. These features are used in this thesis to perform the DG integration issues related to voltage, fault level current, frequency, and harmonics. The results are compared with the UK legislative framework and evaluated whether the variations are within the permitted limits.

1.5. Thesis outline

This thesis includes five chapters and the order given below.

Chapter 1 – Introduction

This chapter provides the background of the thesis and explains the problems intend to investigate. Also, the main objectives established, and described the adopted methodologies and the thesis outline.

Chapter 2 – Literature Reviews

This chapter gives a detailed description of the distributed generation, conventional electrical network, and how the introduction of the distributed generation changes the traditional power network system. Also, it describes the growth of PV and wind distribution technologies and outlines the importance to study about the DG integration. In addition, this chapter illustrates the different distributed generation technologies with a much more detailed study about the mostly used PV and wind generation techniques. Later, a comprehensive study about the technical challenges of DG implementation is presented and explains the background of the problems with the help of numerous research papers. Also, briefed the UK recommended variation limits on the electrical parameters.

Chapter 3 – Methodology

This chapter provides a detailed explanation of the chosen distribution network, and the software used for the simulation to study the impacts of DG integration on the grid. Also, illustrates the different procedures and methodologies adopted to build the models. In addition, the chapter details the various tests performed on the models to study the DG penetration impact. Finally, it ends with the explanation of the different scenarios used in this thesis for the DG integration studies.

Chapter 4 – Simulation Results and Discussions

This chapter presents the simulation results carried out on the software based on the selected scenarios. The results shown based on the different tests such as load flow analysis, short-circuit fault level, transient and harmonic analysis conducted in this thesis. Also, provides the detailed interpretation of the results of each of scenarios. The end of this chapter highlights the key outcomes based on the different results.

Chapter 5 – Conclusions and Future Work

The final chapter presents a summary of the thesis outcome. Furthermore, outlines a recommendation for the future work by considering the limitation of this thesis and possible extension from the current study.

2. Literature Reviews

2.1. Introduction

This chapter includes learning from the various literature that have covered to study the distributed generation and its effect on the grid. Some of the main topics covered in this chapter are a review of the distribution network and how it differs from a traditional system. Also, briefed some of the commonly available distributed generation technologies with a more detailed study about the solar and wind farm electricity generation. In addition, some of the possible impacts on the network due to the DG integration are identified and explained the root cause and its influence on the grid. In the end, a short study on the UK recommended standards regarding the impact level have described. It is used to evaluate the simulation results.

2.1.1. Distributed generation concepts and definition

Traditionally, an electrical power system network consists of four different stages such as generation, transmission, distribution, and consumption. Electric generation is the place where electricity produced by using different technologies and are usually close to the primary energy resource locations (e.g.: - coal mines or water reservoirs). The consumption is the last stage of the network where a consumer uses this generated electricity. Normally, as the consumer is located far away from the generation places, electricity requires to supply through the diverse network such as transmission and distribution network. This includes a high voltage (HV), medium voltage (MV), and low voltage (LV) networks. The different voltage levels have achieved with the help of a transformer and have connected by different types of equipment such as a circuit breaker, and the electricity transmitted through the overhead and underground cables. Normally, the distribution network is designed to operate radially. In a radial network, the power flows in one direction and is from the higher voltage levels to the low voltage levels at the consumer end. A traditional conception of the electrical power supply network is given below in figure 2-1.

In the UK, the voltage levels at the power network vary depending on the purpose; the transmission voltage level is ranging from 400 kV to 275 kV whereas the distribution voltages are in the range of 132 kV to 230 V. The structure of a UK power supply industry (ESI) has shown in figure 2-2.

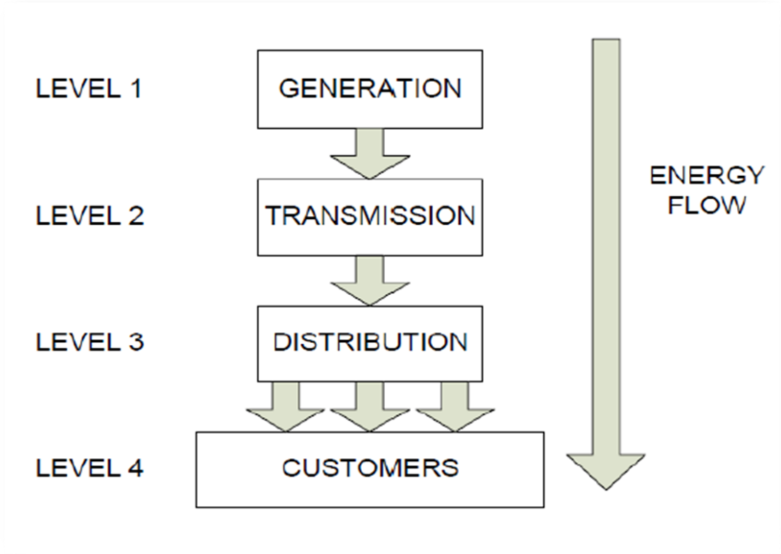

Figure 2-1 A traditional electrical power supply network block diagram (Vignolo & Zeballos, 2002)

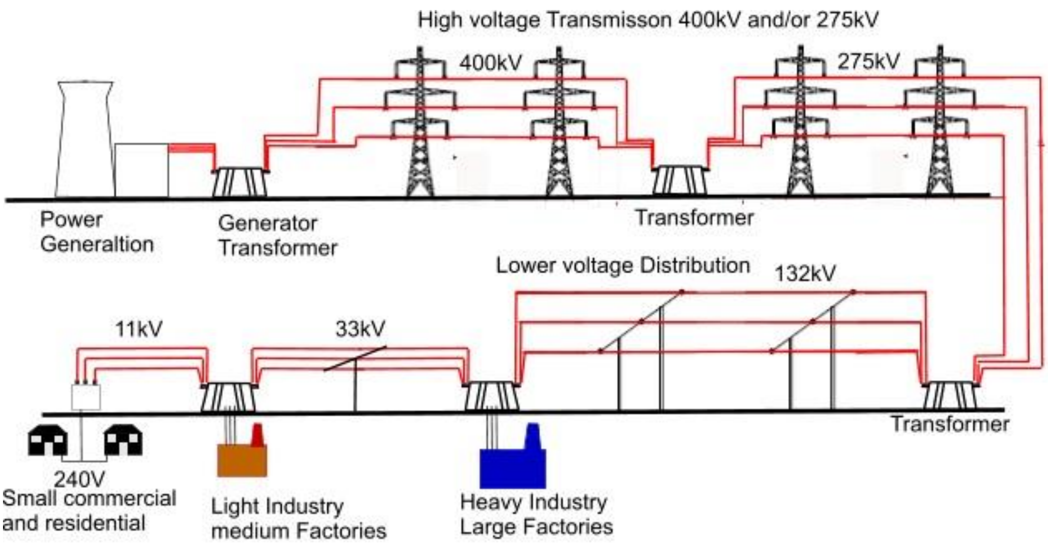

Figure 2-2 The UK electricity supply industry structure (UK Parliamentary, 2001)

Nowadays, the electricity generation is not only limited to one location but also the energy demand met by a combination of generation mix from the centralized traditional plants as well as the distributed sources. The evolutions in technology, environmental policies of governments, and the expansion of electricity and finance markets are some of the main reasons for the development of such distributed generation (Vignolo & Zeballos, 2002). The increasing use of the renewables to reduce the environmental pollution can be considered as the main driving force for the rapid expansion of the distributed generation in the world. The term "distributed generation" includes all use of small electric power generations. It can locate either on the utility system or at the site of a customer or at an isolated site which not connected to the main electrical power grid (Willis & Scott, 2000). The large-scale distributed generators are located either at the LV or MV side. The traditional distribution network was considered as a passive network as this network doesn't have generators units, and the power flows in one direction from high voltage levels to the lower levels like the water flows. However, with the introduction of the distributed energy generations, the electricity network cannot view as a passive system, and it becomes an active system. It means that the integration of DG at different voltage levels allow the power to flow in the opposite direction of the conventional systems as well; that is, from low voltage levels to high voltage levels (Revuelta, et al., 2016). The new conceptional electric supply network has given in below figure 2-3.

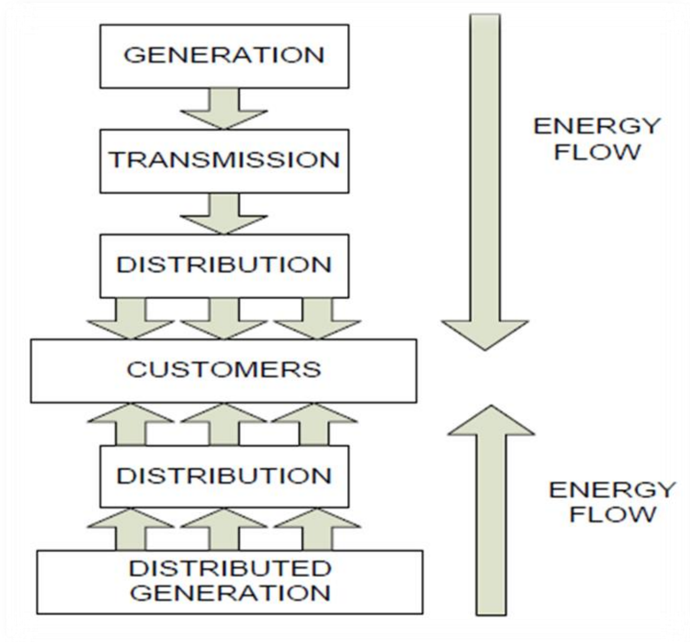

Figure 2-3 Electric supply network with DG (Vignolo & Zeballos, 2002)

There are many definitions available for the distributed generation. According to the Institute of Electrical and Electronics Engineers (IEEE), the distributed generation defined as "the generation of electricity by facilities sufficiently smaller than central generating plants as to allow interconnection at nearly any point in a power system. A subset of distributed resources" (Dondi, et al., 2002). Despite there is no complete definition of DG, the main features of it can be established as (Revuelta, et al., 2016):

- It connected to a distribution network.
- It is common that some part of the generation used by the same facility, and the remaining unwanted part exported back to the grid.
- There is neither a unified planning nor a centralised dispatchability for such generation.

The distributed generation resources involve renewable energies as well as cogeneration systems (CHP). The renewable energy is the energy from naturally available resources such as sunlight, wind, tides, waves, biomass, geothermal heat, etc., and cogeneration systems make use of both electricity and heat. The heat from the cogeneration system can employ for district schemes or the space heating of the same plant. According to the installed size, the distribution system has divided as given in below table 2-1.

Ratings	Categories
1W < 5kW	Micro-distributed generation
5kW < 5MW	Small distributed generation
5MW < 50MW	Medium distributed generation
50MW < 300MW	Large distributed generation

Table 2-1 The categories of DG based on ratings (Ackermann, et al., 2001)

Some of the main advantages (Thong, et al., 2005) identified for the DG are:

- The main idea of a DG to increase the reliability of the power supply to the customers by using the locally available supply. Hence, reduce the transmission as well as the distribution energy losses via power networks, and avoids the black-out due to insufficient conventional electric generation. The DG can be utilised effectively in remote areas or in times of peak demand, where, it might be a cost-saving solution (for instance, electricity for an island).
- The connection of DG to the grid could improve the voltage profile and power quality of the system, and often support the voltage stability. Therefore, the systems can withstand higher loading conditions, and slows down the new construction or modifications of the transmission or distribution systems.
- The payback period and construction cost of DGs are less compared with the traditional systems such as coal or nuclear power plants. Also, the increase in efficiency is achieved especially with CHP.
- Unlike the conventional systems, most of the DG technologies are helping to reduce or eliminate the emission of harmful gases such as the carbon dioxide, nitrous oxide, and other greenhouse gases.
- In many countries including the UK, the governments are subsidizing the renewable energy development, and it also creates an additional income opportunity for the

public. For instance, currently, in the UK, as per the Feed-in Tariff[1] (FIT) government scheme, any solar PV of a capacity <10 KW receives an income of 4.01 p/kWh, and between 10-50 kW, it is 4.25 p/kWh. In case of wind (<50 kW), hydro (<100 kW), CHP (<5 kW) the generation tariffs are 8.46 p/kWh, 8.07 p/kWh and 14.52 p/kWh respectively (Energy saving trust, 2018).

The DG is closely related to the use of renewables, and among the renewables, solar and wind resources are employing widely in the world. The controlling of many such distributed resources makes new challenges to a safe and efficient operation of electrical networks. The problem partly solved with the introduction of microgrids, where such entities coordinate the renewable resources in a more decentralized way so that less controlling related burden on the main grid and maximising benefits from renewables (Hatziargyriou, et al., 2007). The concept of a smart grid defined as "a type of self-managing network with dynamic optimization techniques that uses real-time measurements to minimize losses, to maintain the voltage levels, to increase security, and to improve the system management" (Revuelta, et al., 2016). The data collected by smart grid and other associated subsystems allow the operator to quickly identify the best approach to solve the problems in the network.

The below section describes the major renewable technologies, PV and wind in detail and some of the other distributed generation techniques.

2.2. The wind power technology

As wind power considered as one of the primary sources of renewable energy the electricity formation from wind has been growing rapidly. As per the latest Global Wind Energy Council (GWEC) statistics, the cumulative global installed wind capacity had reached 539.7 MW (GWEC, 2017). Both onshore and offshore wind generation is expected to grow rapidly. The onshore wind is a proven and mature technology, and with advancement in the technology over the last few years, the electricity produced from sites with lower wind speed has increased. Moreover, the wind turbines have become longer with taller hub height and a larger rotor diameter to generate more power. The deployment of the wind turbine in sea lakes showed better use of wind resources than at land-based sites (IEA, 2018), and it resulted in rapid growth of offshore wind turbines. The below statistics (Figure 2-4 and Figure 2-5) shows the global trends of wind power generation.

[1] Feed-in Tariffs (FITs) is a UK Government program that encourages the use of renewables-based technologies (Energy saving trust, 2018).

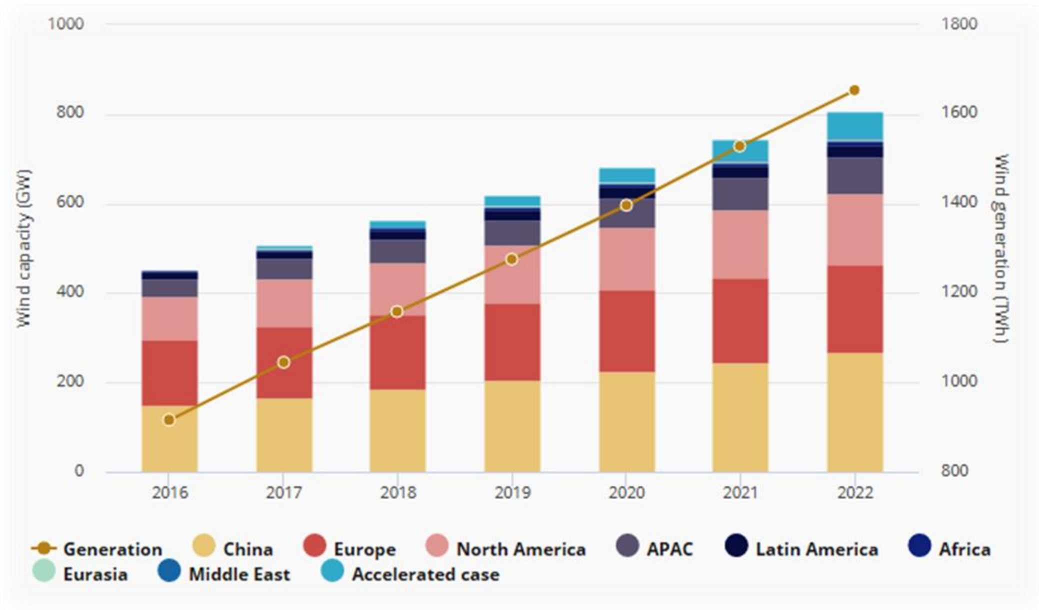

Figure 2-4 Onshore wind generation and cumulative capacity by region (IEA, 2018)

Figure 2-5 Offshore wind generation and cumulative capacity by region (IEA, 2018)

In the UK also witnessed similar trends; both offshore and onshore wind generation rose by 27 % and 37 % respectively in 2017 compared with a year earlier (UK government statistical press release, 2018). As wind considered as the major renewable resource in the UK, the growth is mainly because of the government policies to increase the share of energy consumption from the renewable resources.

As the share of electricity generation from wind is expecting to increase in the upcoming years, it is necessary to study and understand the possible integration issues because of such rapid growth.

2.2.1. The wind power system

The below block diagram (Figure 2-6) represents the major components of a wind power system.

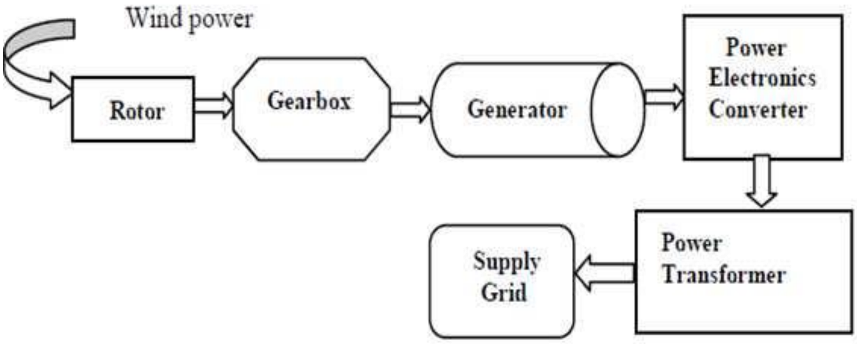

Figure 2-6 A typical wind power system components (Pandey, et al., 2012)

The wind power is used to turn the blades around a rotor. The rotor is connected to the generator via a gearbox/shaft, and it spins a generator to produce electricity. Thus, a wind turbine utilised the kinetic energy from the wind and converted to electrical energy. The output of the wind turbine (Revuelta, et al., 2016) is given by

$$P = \frac{1}{2} C_P \rho V^3 A$$

Where,

P – The power in watt (W);

C_P – Power coefficient, a measure of the effectivity of the rotor aerodynamics;

ρ – The air density (1.25 kg/m^3)

V – The wind speed in m/s;

A – The swept area of rotor disk in m^2

Thus, the generator produces an AC output; but, because of the fluctuating nature of the wind, the AC power needs to convert to the DC power, and later, it turned back to AC with the help of power electronics converters (Blaabjerg, 2012) before integrating with electrical grid. Also, with the help of a power transformer, the voltage stepped-up according to the network grid. The different power curve regions of a wind turbine system according to the wind speed has given in figure 2-7.

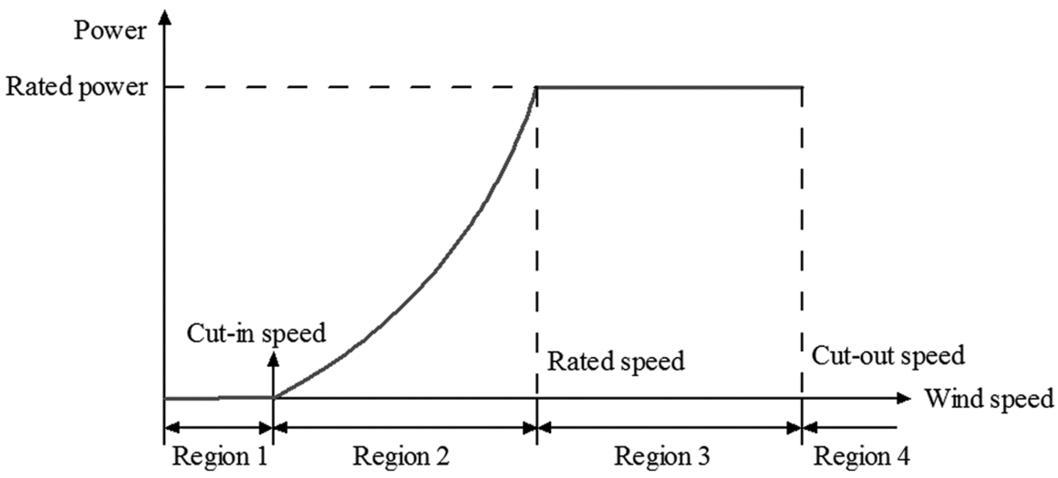

Figure 2-7 The control regions in a modern wind turbine. (Chena, et al., 2018)

In the region 1, the wind speed is too low below the cut-in speed, and hence, the generation is zero, and the turbine is in standby mode. The situation is same in case of high wind speed, i.e. in region-4, where the turbine stops to prevent the damage. In region 2 where the wind speed is higher than the cut-in speed and below the rated speed, the rotor is regulated to achieve maximum blade efficiency and produce the maximum power output. In the case of region 3, when the speed is between the rated and the cut-out speed, the wind turbine produces the entire turbine rated power.

2.2.2. The different wind turbine types

A concise explanation of the different wind turbine generator (WTG) topologies provided below.

a) Type 1 WTG:

Normally, type-1 WTG is pitch-regulated and drives by squirrel cage induction generator that directly coupled to the grid (Fox, et al., 2007). As the wind turbines always work at approximately constant speed, these types of WTG generally called as fixed speed wind turbine. A capacitor bank is also used to improve the power factor by reactive power compensation (Li & Chen, 2008). A typical type 1 WTG system has shown in figure 2-8.

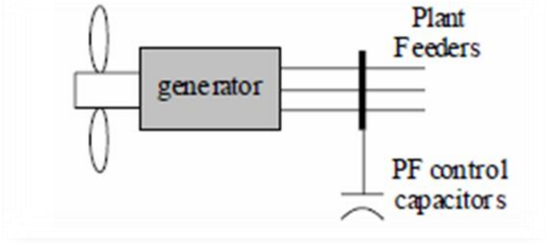

Figure 2-8 Type 1 WTG (Muljadi, et al., 2010)

b) Type 2 WTG:

In this type, wound rotor induction generator is used instead of the squirrel cage type, and whose rotor winding is brought out via slip rings and brushes. An external rotor resistance is electronically modulated to control the speed (Fox, et al., 2007). The energy extracted from the external resistor dumped as heat loss in the external resistance (Li & Chen, 2008). Here also, the capacitor bank is used for reactive power compensation to improve the power factor. A typical type 2 WTG system has shown in figure 2-9.

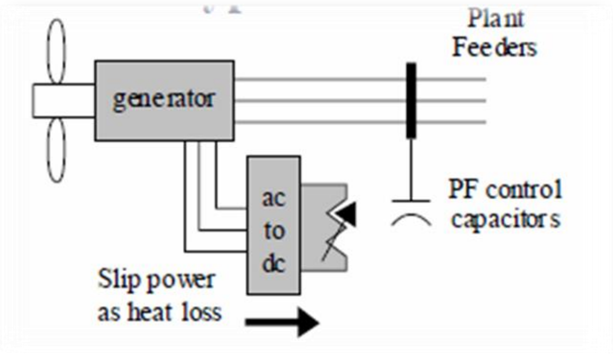

Figure 2-9 Type 2 WTG (Muljadi, et al., 2010)

c) Type 3 WTG:

This configuration is known as DFIG (doubly fed induction generator). The turbine is pitch-regulated and features a wound rotor induction generator with a partial-scale power converter. This AC/DC/AC power electronics converter is connected between the rotor terminals and grid as shown in figure 2-10 (Li & Chen, 2008). The generator stator winding directly coupled to the grid. The converter circuit, through injecting a controllable voltage at the rotor frequency a variable speed operation of the wind turbine is resulted (Holdsworth, et al., 2003). The power converters can be used to provide the required reactive power compensation, and for a smooth grid connection. As the rating of the power converter is around only 25-30 % of generator capacity, it makes this type more attractive and popular from an economic point of view (Li & Chen, 2008). A typical type 3 WTG system has shown in figure 2-10.

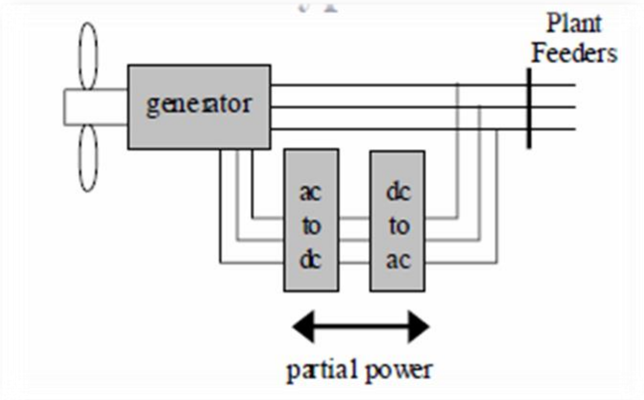

Figure 2-10 Type 3 WTG (Muljadi, et al., 2010)

d) Type 4 WTG:

In type 4 WTG, a pitch regulated turbine, and an induction or synchronous type generator used. It also utilises an AC/DC/AC power converter and through which the entire generator power processed. Like type 3, type 4 also supports faster active and reactive power over a wide range of speeds. The major distinction with the previous type is the generator rotates at a low speed because of the direct connection of the generator rotor with the hub of the turbine rotor (Li & Chen, 2008). Therefore, the generator is usually designed with a larger diameter and small pitch to deliver more torque (Dubois, 2004). A typical type 4 WTG arrangement shown in below figure 2-11.

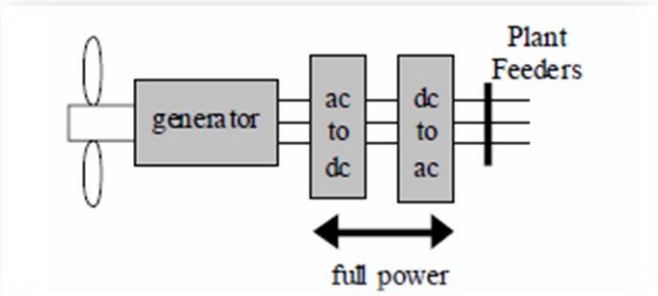

Figure 2-11 Type 4 WTG (Muljadi, et al., 2010)

2.3. The solar power technology

Solar power technologies use sunlight to convert into useful energy forms. It utilises both light and heat from the sun. Such energies from sun harnessed by using the various progressing technologies such as "solar heating, solar photovoltaic, solar thermal electricity, solar fuels, solar architecture and artificial photosynthesis" (Hyder, et al., 2018). Among these, the photovoltaic systems are considering as most popular applications. The main advantage of solar PV is that the manufacturing of PV's can be done in large plants as well as for small areas. Hence, it allows large scale deployments as well as deployment in very small quantities (IEA, 2018). The significant drop in the cost of solar PV system in the last decade can be considered as the main driving force for the substantial expansion of the global PV market (Nemet, et al., 2017). The total solar PV capacity has reached almost 300 GW and generation crossed over 310 TWh in 2016 (IEA, 2018). The utility-scale installation accounted for a major part of it, that is, 55 % and the rest is in distributed applications that include "residential, commercial and off-grid" (IEA, 2018). The photovoltaic is expecting to lead renewable electricity capacity growth and the anticipated global trend for the next few years given in figure 2-12

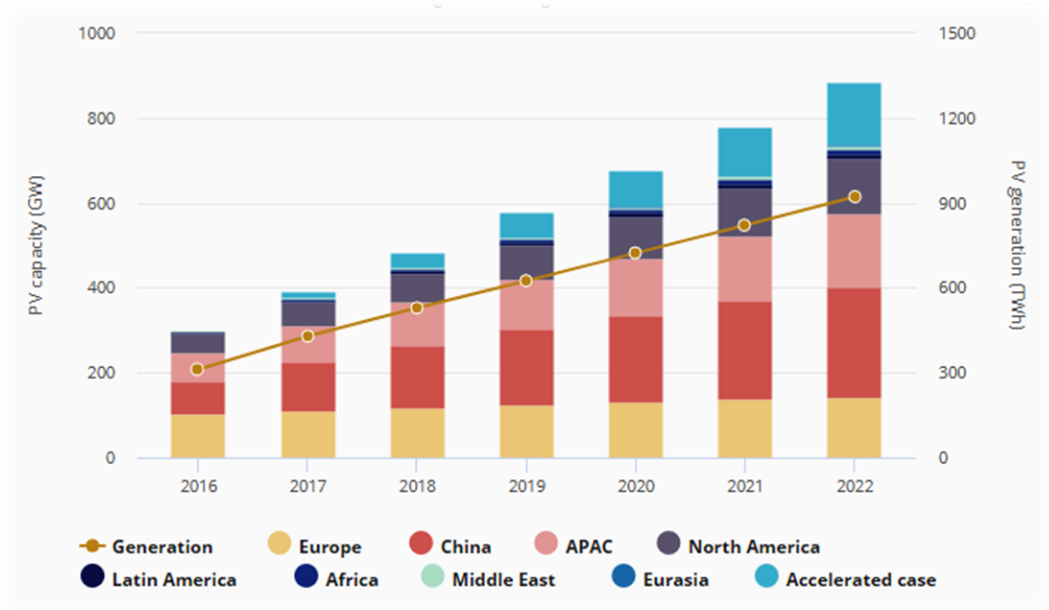

Figure 2-12 The solar PV generation and cumulative capacity by region (IEA, 2018)

In the UK also witnessed similar trends; the generation from solar photovoltaics increased by over 10 % in 2017 compared with a year earlier (UK government statistical press release, 2018). The UK witnessed a rapid growth of solar PV in the recent years, and in 2016, "solar photovoltaic generation showed the largest absolute record increase of the renewable technologies, rising by 2.9 TWh (38 %) to 10.4 TWh in 2016" (BEIS, 2017).

As the share of electricity generation from PV also is expecting to increase in the upcoming years, it is good to study and understand the possible integration issues because of such rapid growth.

2.3.1. The solar PV system

The photovoltaic (solar cells) are the "electronic devices that convert sunlight directly to the electricity" (IEA, 2018). This method called the "Photovoltaic effect"[2]. Depending on the materials used the PV technologies usually classified into three generations. The first generation uses "wafer-based crystalline silicon technology", the second generations based on "thin-film PV technologies" and the third include technologies such as "concentrating PV and organic PV cells that are still under the demonstration" (IRENA, 2012). A typical grid connection scheme of a PV panel system has given in below figure 2-13.

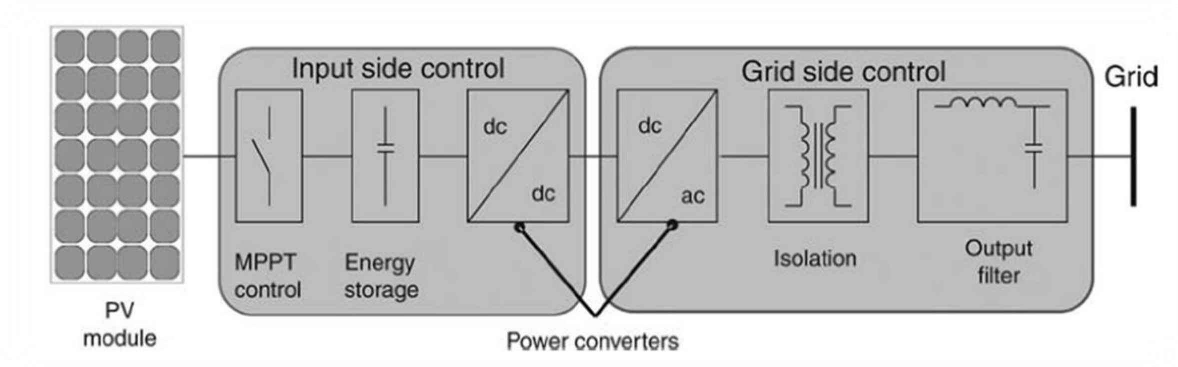

Figure 2-13 Grid connection scheme of a PV plant (Revuelta, et al., 2016)

As the output from the single photovoltaic cell is typically around 1 to 2 W, to generate much higher output, many PV cells are grouped in series and parallel combination to form a PV module. Then, several such PV modules are electrically connected again in the series-parallel method as in the figure 2-13 to generate the power at the required levels. The approximate power output from a PV panel is given by the below equation (Revuelta, et al., 2016).

$$P_{mp} = \frac{G}{G_{ref}} P_{mp,ref}\left[1 + \gamma\left(T - T_{ref}\right)\right]$$

Where,

P_{mp} - The maximum power outputs.
G - The incident irradiance.
G_{ref} - 1000 W/m².
$P_{mp,ref}$ - The maximum power output under standard testing conditions.

[2] The Photovoltaic effect is "when two different (or differently doped) semiconducting materials (e.g. silicon, germanium), in close contact with each other generate an electrical current when exposed to sunlight. The sunlight provides the electrons with the energy needed to leave their bounds and cross the junction between the two materials. This occurs more easily in one direction than in the other and gives one side of the junction a negative charge with respect to the other side (p-n junction), thus generating a voltage and a direct current (DC). PV cells work with direct and diffused light and generate electricity even during cloudy days, though with reduced production and conversion efficiency" (IRENA, 2012)

γ - The maximum power correction for temperature.
T - The measured temperature.
T_{ref} - The temperature for standard testing conditions reference (25°C).

The DC converter at the output of the PV panels (shown in figure 2-13) used to adjust the voltage to proper levels from the panels. The DC/AC converter is connected to convert the DC output to AC and to make the voltage and frequency according to the grid conditions. The output voltage of the module limited by the increased cell temperature. Hence, to obtain maximum power output, a "maximum power point tracking (MPPT)" circuit is used with storage elements, and those are attached with the DC/DC converter (Jenkins, et al., 2010). A typical voltage-current characteristic of a PV module has given in figure 2-14. The isolation transformer shown in the figure 2-13 at the grid side is used to avoid the injection of DC into the network, and a filter circuit is used to remove the harmonic components (Jenkins, et al., 2010).

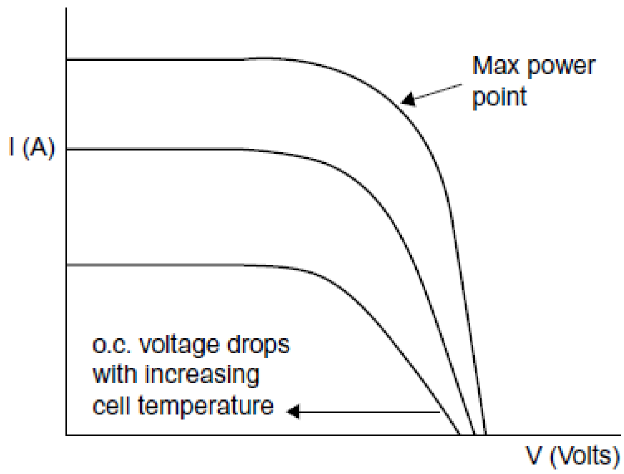

Figure 2-14 Typical voltage/current characteristic of a PV module (Jenkins, et al., 2010)

2.4. Other Distributed generation technologies

Some of the other commonly used DGs are given in this section

2.4.1. Micro Gas Turbine (Cogeneration or CHP)

A micro gas turbine (MGT) is composed of a "centrifugal compressor, radial turbine, combustor, and recuperator" (Kim, et al., 2018). A rectifier and inverter have connected to the output of the generator. The is the most commonly used design is the compressor and turbine installed on a single shaft and has shown in below figure 2-15.

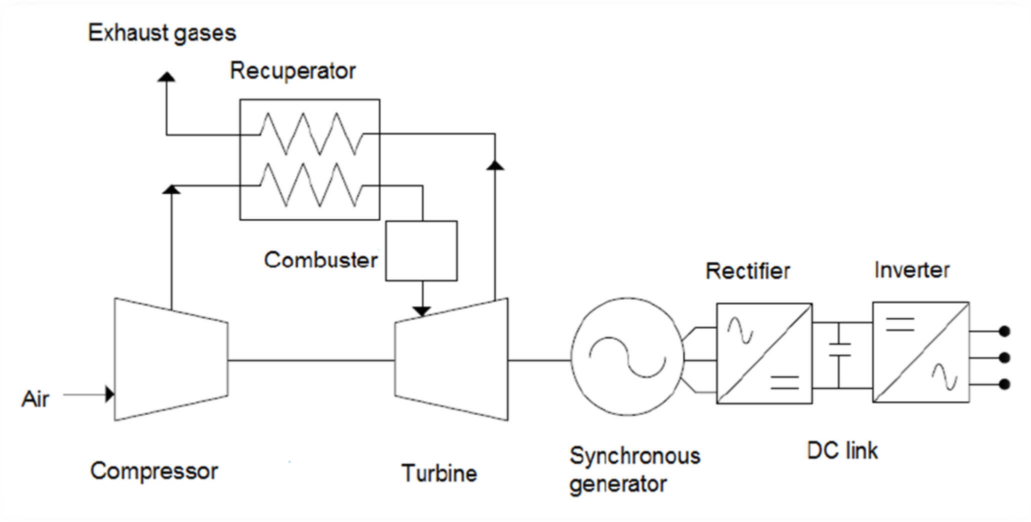

Figure 2-15 A micro gas turbine scheme (Kim, et al., 2018)

A micro-turbine utilises the flow of gases to convert the “thermal energy into the mechanical energy”. The combustible gas is mixed with air and compressed in the compressor. Later, the compressed combusted mixture at high temperature and pressure drives the turbine, and it impulses the generator to generate the electricity. The recuperated unit recovers some of the exhaust steam and transfers it to air flow at the inlet. Hence, it raises the temperature of the inlet air supplied to combustors. Further, the recovered exhaust steam can use for the cogeneration schemes, where recuperator outlet gas is transferred into a heat exchanger to make hot water, and then for the space heating purposes (Pilavachi, 2002). To achieve the required voltage and frequency level before connecting to the grid, the output from the generator converted to DC, and later, turns it back again to AC. Some of the advantages of the MGTs are “larger specific power, noise reduction, and emit much fewer pollutants, especially NOx” (Kim, et al., 2018)

2.4.2. Fuel Cells

Hydrogen can be considered as an important clean renewable energy source as it is widely available in the universe. A fuel cell uses the hydrogen potential and generates electricity. The process involved in the electricity generation process is the same as the battery, “the conversion of the chemical energy to the electrical energy.” A typical fuel cell scheme that usually available shown in figure 2-16.

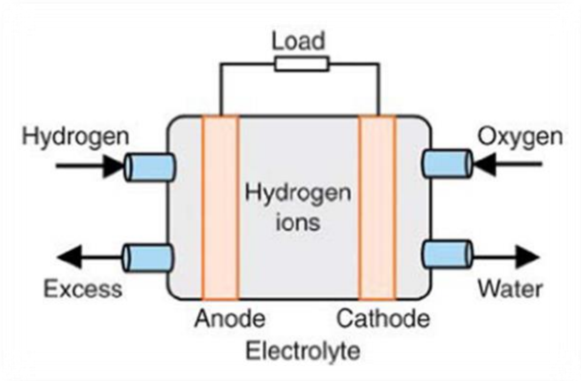

Figure 2-16 The fuel cell scheme (Revuelta, et al., 2016)

In a fuel cell, under the monitored and controlled condition and in the presence of a catalyst, the incoming hydrogen at the “anode” is divided into “protons and electrons.” Then, the protons allowed to pass to the cathode through an electrically isolated membrane, but, “the electrons are forced to flow through an external circuit to generate the energy” (Revuelta, et al., 2016). In the catalyst of the cathode, the “oxygen molecules react with electrons and protons to produce water.” Unlike the battery, for a fuel cell, the hydrogen and oxygen supplied as a constant flow from outside. Thus, generates electric power continuously without interruptions. As the output from the fuel cell is constant, an inverter has used before connecting to the grid. Normally, a single cell provides very less voltage (less than one volt), and therefore a group of fuel cells is normally "stacked" together to increase the power output. Some of the advantages of a fuel cell are “high efficiency, low pollution, quiet operation, etc." (Metra, 2015).

2.4.3. Small Hydro Generation

The conversion of the potential energy of water into the electrical energy is a matured technology and widely spread throughout the world. Nowadays, the trend is on the small hydropower schemes. In general, currently, three different types are most common in the world (IEA, 2018). First, the “traditional big reservoir type hydro plants”; where the water stores in reservoir and electricity produced as per the demand by utilising the potential energy of water in the reservoir. Second, the “run-of-river hydropower plants”; where the electricity produced mainly from the available flow of water These types include some short-term storage or “pondage” to have some flexibility for a day or few hours. Last is the “pumped storage plants”; where water pumped from the low reservoir to upper reservoir when “supply exceeds the demand” or at times of least power cost, and when the “demand exceeds the supply” the water flows back from the upper reservoir through turbines to generate electricity.

The output power of a hydraulic turbine (Jenkins, et al., 2010) is given by

$$P = QH\eta\rho g$$

Where

P – The output power in Watts
Q – The flow rate of the water (m^3/s)
H – The effective head of the reservoir (m)
η – The overall efficiency of the plant
ρ – The density of water (1000 Kg/m^3)
g – The acceleration due to gravity (m/s^2)

Nowadays numerous researches are continuing to achieve more efficient turbines and for the maximum exploitation of variable flow rates and heads.

2.5. Contrary Impacts of DG on a distribution system

The below section illustrates some of the common issues and its root causes related to the DG integration with the grid.

2.5.1. Impact on voltage regulation

Distributed networks originally designed to operate radially without any generating sources either at the distribution lines or at the customer premises. The introduction of DG can deteriorate the effectiveness of the voltage regulators in the system in charge of handling voltage variations and in case of failures within the system (Casavola, et al., 2011). A distribution network voltage normally regulated with "load tap changer (LTC)" at the substation, and with supplementary line regulators as well as switched capacitors on the feeder (Barker & Mello, 2000). The voltage regulation is normally performed based on the power flows from a substation to the customer loads. The introduction of DG may result in the change of the voltage profile because of the variation in the direction or the magnitude of the power flow. The figure 2-17 shows an instance where the introduction of distributed generations changed the voltage profile at the feeder. In this case, a DG unit introduced at the downstream of the voltage regulators. The changes in the magnitude and direction can create problems for the all the types of equipment used within the feeder system, and it could impact the supply voltage at the customer ends. Thus, it creates safety-related problems within the power system.

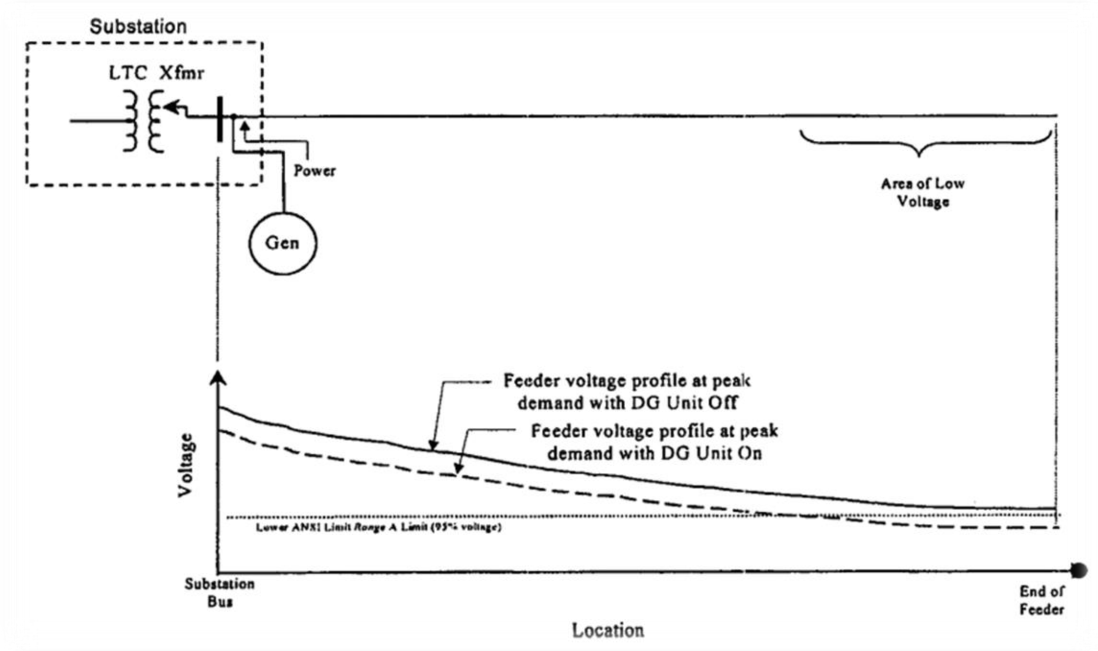

Figure 2-17 Comparison of change in voltage profile with and without DG units (Barker & Mello, 2000).

It has shown in the above figure that the addition of DG reduced the voltage magnitude on the feeder. This misleads the regulator into setting a lower voltage than it originally required at the consumer levels. Thus, the DG reduces the “observed load at the line drop compensator control, and it makes the regulator to set less voltage at the end of the feeder” (Barker & Mello, 2000). This makes negative consequences on the system. Therefore, it is necessary to introduce an additional regulator controller or the movement of DG into the upstream direction to resolve the problems.

There are chances of voltage regulation problems when the DG penetration become significant compared with the feeder capacity. For instance, when the DG becomes greater than 30 % of the feeder capacity, and if it suddenly disconnected following a fault, the load becomes significantly higher for the feeder and LTC settings to handle. (Akorede, et al., 2010). It leads to a condition as shown in the figure 2-18. Even if the circuit breaker has acted suitably to clear the fault, the situation in the figure could remain for a period of 5 minutes or more (Akorede, et al., 2010). Under this condition, the voltage at the customer end could sag below the minimum permitted level for the period until the voltage regulation equipment reacts. This can cause damage to the equipment due to the excessive low voltage.

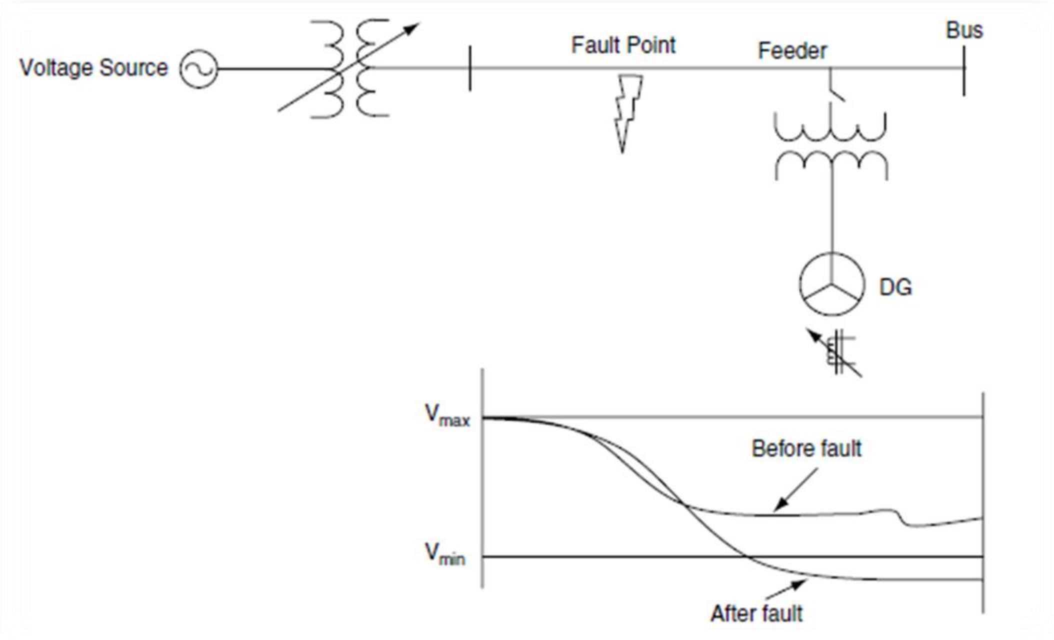

Figure 2-18 The changed voltage profile in case of a fault clearance at the distribution feeder with DG (Akorede, et al., 2010)

The installation of the DG may also result in the higher voltage at the customer premises. For instance, a small DG system which shares a “common distribution transformer” with several customers may cause the high voltage at the secondary side (Barker & Mello, 2000). This is mainly due to the reverse power flow, and such voltage swell above the limit may cause damage to equipment at the customer end. During the normal conditions, that is without DG, the voltage at the customer end is lower than the primary side of the transformer. The connection of DG causes power to flow in a reverse direction to nullify this normal voltage changes and could rise voltage at the secondary side than the primary side of the distribution transformers (Barker & Mello, 2000).

Thus, the DG penetration impacts the voltage profile, and any potential application requires deep analysis prior to the installation to ensure that no customers impacted (Barker & Mello, 2000).

2.5.2. Impact on power quality

As explained in the previous section, the bi-directional power flow and complex power (especially the reactive power) management may create fluctuations in the power flow, and it could affect the quality of power. The large-scale distributed generation switches, the sudden start or stop of the distributed generators integrated with the distribution power network also creates voltage fluctuations (Kling & Slootweg, 2002) such as flickering, dips and steps outside the permissible limits on the network of other customers (Akorede, et al., 2010). Harmonics is the other noted problem due to the DG integration.

Harmonics creates distortion on the fundamental sinusoidal wave and introduces additional issues on the power network. “Harmonics is a sinusoidal component of a period of a wave having one frequency which is multiple of the fundamental waveform” (Nasrul & Firmansyah, 2015). Usually, the harmonics divided into even and odd harmonics. In most of the cases, the even-numbered harmonics are negligible. The reason is the resultant harmonics is the even multiple of the fundamental components and generates symmetrical waveforms as the original waves. However, in the case of odd harmonics, the effects are significant as it changes the fundamental sinusoidal waveform characteristics as shown in the below figure 2-19. The different odd harmonics and its influence on the fundamental waveform have also presented in figure 2-19.

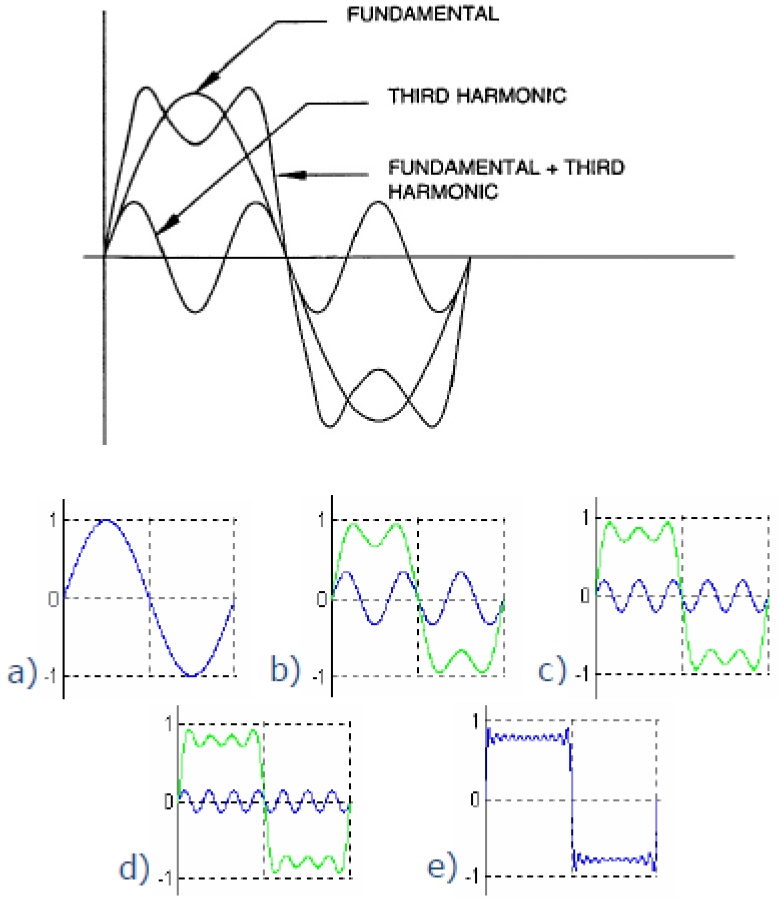

Figure 2-19 The odd harmonic effects on the fundamental waveform; wave distortion due to 3rd (b), 5th (c), 7th (d) and higher harmonics(e) (Nasrul & Firmansyah, 2015).

In general, harmonics created in the DG power network is either because of the power source itself such as synchronous generators or due to the power converter technology such as an inverter that used for the interconnection. In addition, the harmonics can be created depending on the transmission line parameters, transformer configurations, and other types of equipment used in the power network such as protection devices. The type and severity of the harmonics introduced in the distributed generation systems are depending on “power converter technology and the interconnection configuration” (Barker & Mello, 2000). Depending on the design of the generator windings, core non-linearities, grounding, and other factors may create harmonics and distort the waveform as shown in figure 2-19. For instance, the synchronous generators often designed with winding pitch[3]of 2/3 to limit the of 3rd harmonics production. However, such machines have lower impedance against the flow of harmonics current from other sources that are connected parallel to it (Barker & Mello, 2000). The “grounding arrangement of generator and transformer” is the key to decrease the penetration of harmonics in the feeder because such arrangement can reduce or block the harmonics, especially the most problematic third harmonics (Barker & Mello, 2000).

Renewable sources are integrated with the grid through PWM inverters and are controlled to behave as current sources to inject active current into the grid. In case of a wind inverter, it is required to stay under very low voltage condition as well as to regulate the voltage at the point of common coupling due to the variability of the resource (Sun, 2012). Harmonics resonance has been found an increasingly common problem at such interface between grid and inverters. The parts of equipment connected can be damaged by over currents or over voltages that created due to the resonance following harmonics creation. The root cause of such a problem is that “such inverter exhibits capacitive output impedance with its current control bandwidth” (Sun, 2012). In the case of a grid with many DGs, when the supply voltage of the grid distorted by non-linear loads, the inverter output current may also get deteriorated. Therefore, the resulting distorted current increase the voltage harmonics in the grid (Wang, et al., 2011).

Some of the main effects due to the harmonics are “equipment damages, vibrations and torque pulsations on the rotating machines, additional losses on all machines or devices or network elements etc., increase in stress on cables, distortion of operating characteristics of the protection relays[4], malfunction of the controls systems, etc.” (Louie, et al., 2006).

[3] “Winding pitch is defined as the distance between the starts of two consecutive coils measured in terms of coil sides” (U.A.Bakshi & M.V.Bakshi, 2008).
[4] A relay is designed to trip the circuit breaker when a fault detected.

As per the regulatory standard, any DG installation design should comply the IEEE 519 standard requirements(though each countries limit can vary), and in case of larger DG units, the IEEE voltage distortion limits are also required to meet as explained in Table-3-2 and Table-3-3) (Barker & Mello, 2000). With the introduction of the IGBT technology, it is possible to generate output sine waveforms which satisfy IEEE requirements, and thus, eliminated the high level of harmonics current generation due to the old SCR type power converter technology (Barker & Mello, 2000). It mainly arranged with the suitable design of the external harmonic filter.

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
$< 20^c$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L

where

I_{sc} = maximum short-circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

Table 2-2 The IEEE recommended current distortion limits for voltage between 120 V & 69 kV (IEEE, 2014)

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \le 1.0$ kV	5.0	8.0
1 kV $< V \le$ 69 kV	3.0	5.0
69 kV $< V \le$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Table 2-3 Recommended harmonic IEEE voltage distortion limits (IEEE, 2014)

Where,

h: Harmonics order

PCC (Point of common coupling): "The point in the power system closest to the user where the system owner or operator could offer service to another user" (IEEE, 2014).

TDD (Total demand distortion): "The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50^{th} order and specifically excluding inter-harmonics (A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating), expressed as a percent of the maximum demand current" (IEEE, 2014).

THD (Total harmonic distortion): "The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50^{th} order and specifically excluding inter-harmonics, expressed as a percent of the fundamental" (IEEE, 2014).

2.5.3. Impact on short circuit fault levels

On the occurrence of the fault in the distribution network, the fault current flows into the fault location. This fault current comprised of the current from the connected generation sources as well as the rotating loads at the customer premises such as motors (Boljevic & Conlon, 2008). Typically, this fault current detected by the protection system in the network, and it cleared by circuit breakers or fuses.

Increase in DG penetration could impact the short circuit fault current level of a distribution network. The impacts from a single small DG unit may not be large, but, the sum of many small units or some large units of DG can cause serious problems on the power network. In general, there are three considerations for the fault current (Khan, 2008). The fault current must be below the short time ratings of the equipment, over current equipment sizing should be done properly according to the fault current level, and coordination of relays, reclosers, fuses and other overcurrent devices must be designed based on the fault current limit. For instance, the large short circuit fault current may cause miss coordination or malfunctioning of protective devices like fuses or relays. Hence, those may influence the "reliability and safety of the distribution system" (Barker & Mello, 2000). The below figure 2-20 shows a typical arrangement of a fused lateral methodology on a feeder with a "fuse saving scheme"[5] is used. The addition of DG units could result in the fault current to become large enough so that the fuse unable to coordinate with the feeder circuit breaker before it

[5] Fuse saving scheme is "typically uses a low set instantaneous overcurrent element which will trip the feeder breaker before the fuse branch can blow, and the breaker is then immediately reclosed" (General Electric, 2002).

blows. That may lead to undesirable operation of the fuses, and thus, decreases the reliability on the system.

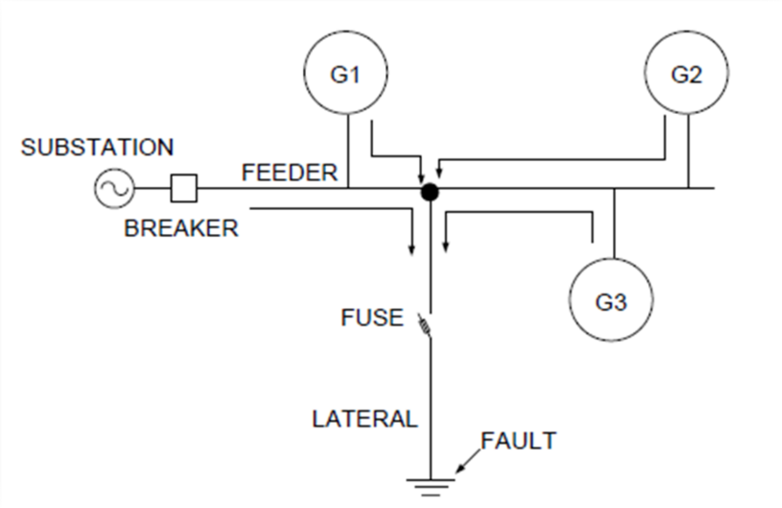

Figure 2-20 Typical fused lateral scheme arrangement with DG units 1,2 and 3 (Barker & Mello, 2000)

The influence of DG on faults depends on the major factors such as the type of DG and the distance of DG units from the fault location. The increased cable impedances over a long distance is likely to reduce the fault current (KEMA Limited, 2005). Hence, as DG distance increases from the fault locations the fault current contribution has become lesser. The presence of a transformer in between the fault location and the contributing DG may also help to reduce the fault level because of the transformer short circuit impedance. Moreover, depending on the configuration of the network between the DG and fault location, the fault current varies as the presence of various paths for the flow of fault current could change the magnitude of the fault current due to the cable impedance and the other equipment's installation (KEMA Limited, 2005). In addition, depending on the method of coupling of DG to power network the short-circuit level varies. The directly coupled DG may contribute more fault current compared with connected systems via power electronics interfaces (KEMA Limited, 2005).

2.5.4. Protection challenges

The risk of network failures on the power system network has increased since the introduction of the distributed generation system because of the dynamic changes in the system impedance as well as the power flow directions. The protection schemes in the unidirectional power flow network were relatively simple. But, the introduction of DG to the existing network forced to make a detailed investigation to achieve enough protection for power system and different network components in the system (Akorede, et al., 2010).

Some of the protection problems barriers are:

a) Unwanted islanding
b) Blinding of protection
c) False tripping of feeders (sympathetic tripping)
d) Ferroresonance
e) Protection coordination issues

a) Unwanted islanding

The unwanted islanding could occur when a single or group of distributed generators continue to energize a portion of the utility network that separated from the main utility system. This separation might be because of an upstream breaker, fuse or switch (Barker & Mello, 2000). For instance, in figure 2-21, a fault leading to an opening of the circuit breaker A. But, the fault current resulted might be insufficient to operate the circuit breaker D and it would result in islanding. Under this situation, the distributed network is left connected only to a small portion of the network and it continues the energization (Akorede, et al., 2010).

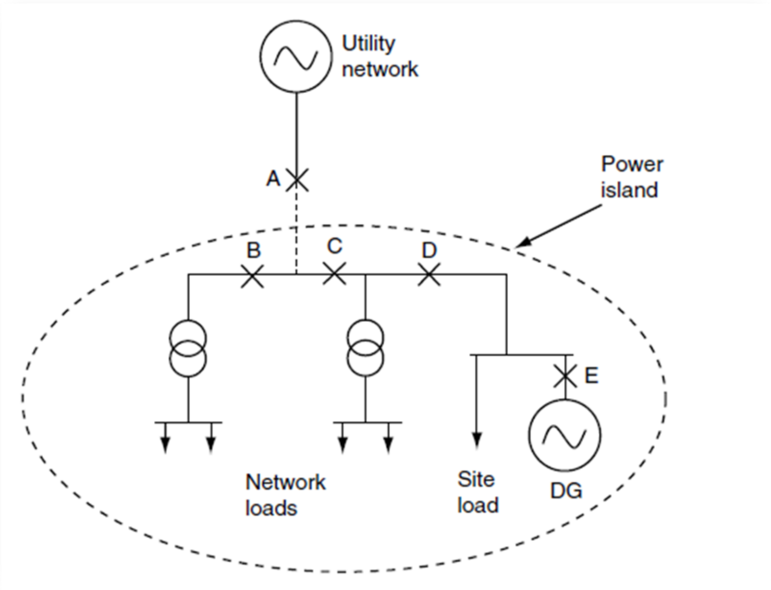

Figure 2-21 An islanding operation situation (Akorede, et al., 2010)

The islanding could result in some critical situation such as the DG sources might subject to exceeding of voltage and frequency allowed limits. This causes serious threats to the public as well as the maintenance operators who exposed to the circuit. The islanding also could end in the damage of equipment due to out-of-phase reclosure, and serious power quality related problems to the utility and the loads. Normally, the islanding can avoid by using “passive” or “active” approach (Barker & Mello, 2000). The “passive” approach uses the voltage and frequency relays to break the circuit when voltage or frequency exceeds the limit. In the case of "active" approach, "tuned" inverter is used to respond in the unwanted frequency conditions. Active anti-islanding is more robust than passive. However, it cannot guarantee protection under some rare situations (Barker & Mello, 2000).

b) Blinding of protection

Blinding is a critical issue as it decreases the protection range seen by a relay (Mäki, et al., 2005), and it might create unwanted problems in the power network such as damage of equipment's, safety problems etc. This may happen when the substation and DG are feeding the fault in parallel as shown in figure 2-22 Because of short circuit impedances, the current flowing through the feeder relay decreased, and there is a high risk that faults with high resistance will go undetected until they turn into larger faults. Hence, the relay becomes non-operational in some part of the network due to blinding. This situation can eliminate by suitable network reinforcements; but, this will increase the overall DG installation cost (Mäki, et al., 2005).

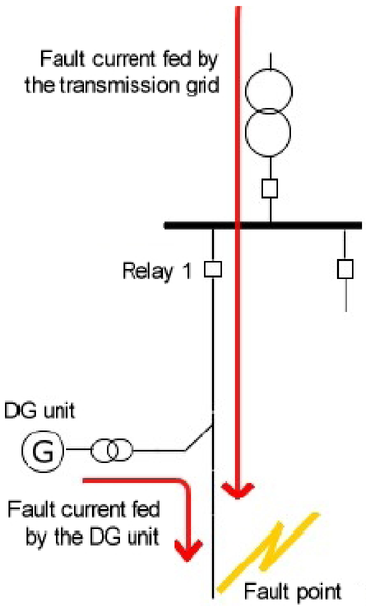

Figure 2-22 A typical protection blinding situation (Mäki, et al., 2005)

c) False tripping

A basic false tripping incident has shown in the figure 2-23. Here, a short circuit has occurred on feeder 1. Ideally, the circuit breaker 1 (CB1 in the figure) alone required to trip; however, the feeder also might trip because of the overcurrent fed by DG unit (Kauhaniemi & Kumpulainen, 2004). This false tripping can solve by "directional overcurrent relays"[6] with few additional modifications in the system. However, it may cause extra costs and difficulties to the network companies.

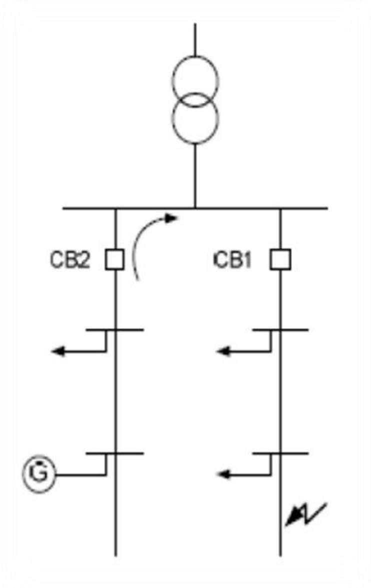

Figure 2-23 A typical false tripping incident (Kauhaniemi & Kumpulainen, 2004)

d) Ferroresonance

Ferroresonance is a special kind of phenomenon that happens when inductance altering with saturation (Akorede, et al., 2010). For instance, in the case of a transformer, when the system capacitance connected in series with the non-linear inductance this phenomenon may occur. Normally, this situation results when switching or single fuse blowing of one or two phases of a three-phase distribution system happens. The fault on the utility system leads to blowing off one or two phases of the transformer. This leads to isolation of the one or two open phases of the transformer at no load on the cable. It makes the cable capacitance in series with transformer inductance as shown in figure 2-24 and the ferroresonance phenomenon occurs (Akorede, et al., 2010). This incident creates various power quality issues such as under and over voltage, and hence, the waveform would be highly distorted. This phenomenon can avoid by using three-phase switchgear on the primary side of the transformer (Akorede, et al., 2010). But, it will increase the overall cost of the system installation.

[6] The relay operates with the help of a circuit breaker that designed to trip depending on the direction of fault current.

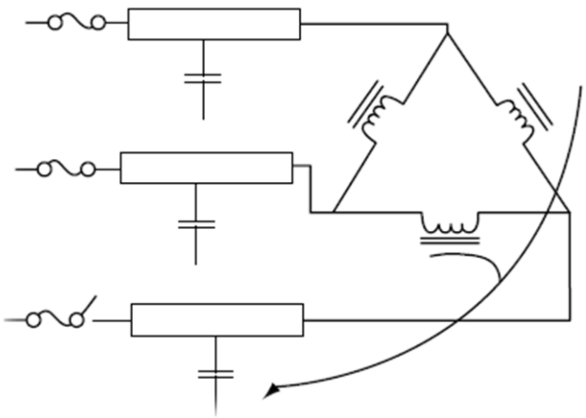

Figure 2-24 The ferroresonance scenario (Akorede, et al., 2010)

e) Protection coordination issues

There are various protection techniques used in the power system to isolate the faulty part from the rest to avoid the numerous electrical problems. At the same time, it provides safety to the customers as well as to the equipment's used in the system. However, when DG's are connected, the current flowing through the protection devices are no longer same, and hence, the coordination of the protection equipment's used in the power network would be difficult to achieve, and in certain cases might be impracticable. The network design is strongly depending on the protection practices in the system. Hence, in sometimes depending on the location, type and size of the DG, the reconfiguration of the existing protection scheme in the power network may be needed.

2.5.5. Impact on losses

The DG can influence the losses on the feeder depending on the location of DG installation. Usually, the DG installation impacts "both active and reactive power flow" (Barker & Mello, 2000). However, the installation of DG can employ in the same way as a capacitor used for the reactive power compensation. On the feeders where the losses are high, a small unit of suitably placed DG with an output of around "10-20% of the feeder capacity" can have a significant positive impact to reduce the system losses (Barker & Mello, 2000). However, for the most of utilities unable to control the location of the DG (especially residential DGs) because of the local customer ownership. In case of large DG penetration, the thermal limit of overhead lines or cables must also need to consider because the DG can inject power that "exceeds the thermal limits" without creating any problem on the voltage profile of the feeder (Barker & Mello, 2000). Hence, power flow analysis must be completed to find the optimum location of DG by considering both voltage and thermal limitations in case of potential DG installations.

2.6. Recommended electrical parameter limits in the UK

Some of the recommended practices in the UK regarding the voltage, frequency, harmonics limits that used to analyse the impact of distributed generation on the distribution network those are relevant to examine the outcome from the model is given below.

- In the UK, "132 kV and lower in England and Wales, or lower than 132 kV in Scotland" is considered as a distribution system (ENA, 2014).
- The distribution network system and any generating plant connection to that network must comply with the UK obligations related to voltage, frequency, harmonics, security, and other voltage disturbances.
- For a voltage below 132kV, "a variation of not exceeding 6 % above or below the declared voltage" is considered as within the acceptable limits (legislation.gov.uk, 2002).
- "A deviation of not exceeding 1 % above or below" the declared frequency is considered as within the acceptable limits (legislation.gov.uk, 2002)
- The short circuit current calculation (ENA, 2015) in the power network due to a short circuit fault must be according to the IEC 60909 standard (Sweeting, 2011).
- The approved total harmonic distortion (THD) level for the system voltage between 22kV to 400 kV at the point of common coupling is 3% (ENA, 2005)

2.7. Summary

This chapter discussed various distributed generation technologies and some of the impacts that might have resulted when integrating DG into the grid. It can be noted that the traditional distribution networks main features have changed from being a passive network to an active network due to the introduction of distributed generation into the electrical network. Hence, it has driven various challenges to the modern network. Therefore, the changes need to analyse and address the issues resulted. This chapter also explained the root cause of some of the impacts. At the end of this chapter, briefed the possible variations limit of main electrical parameters in the distribution network system according to the UK standards. It means that any integration of the DG into the grid should be within those limits, and hence, the outcome from the prototype study models regarding the electrical parameter needs to analyse based on such limits. In the following chapter, the software used, and the methodologies adopted to model the DG to study the integration has explained.

3. Methodology

3.1. Introduction

The different procedures that carried to design and study the impact of distributed generation into the grid given in this chapter. The selection of a distribution system to study the impacts was not a straightforward task. As mentioned in the main introductory section, since it is difficult to model the original UK distribution network by considering the technical and other considerations to design the existing power system, the most viable approach is to use the IEEE distribution test feeders. Numerous researches have based on such test distribution systems and the researchers use these test systems to “provide models of distribution systems that reflect the wide diversity in design and their various analytic challenges” (IEEE, 2017). Therefore, in this thesis, the IEEE 30 bus[7]system is used to study the impacts on the grid while increasing the DG contribution to meet loads. It is mainly because the available distribution level voltage is like the real UK power network. Furthermore, the IEEE 30 bus system can consider as robust, and the parameters used in the model reflects as the representative of a robust region of the UK power network. For an instance, the central belt of Scotland where the power network is strong. The software selected to study the impact is ETAP, one of the best and comprehensive tools available in the current market to study the integrated power system that spans from modelling to operation (etap, 2018).

3.2. The distribution power network system

The single line diagram of the IEEE 30 bus system given in the figure 3-1. In the single line diagram, mainly two different voltage levels are used, 132 kV at the generation side and 33 kV at the load side. As the 33 kV is one of the main distribution levels in the UK (as shown in the figure 2-2), the IEEE 30 bus system has chosen and analysed the impacts on the bus at different renewable penetration levels to the network. The total connected load in the network is 283.4 MW, and the total generation available is close to 300 MW (with conventional generation). The load data at each bus given in below table 3-1 and other technical inputs used (University of Washington, 1999) to build the model are given in Appendix A. The different scenarios have taken by increasing the penetration level of DG, and according to the input of DG, the generator contribution has decreased. Then, different tests are conducted to study the changes in the voltage, frequency, and short circuit current

[7] A common connecting point in an electrical power network

levels after increasing the renewable penetration. Also, conducted a harmonic analysis to study the effect on the power quality. The more detailed explanations given in the below sections.

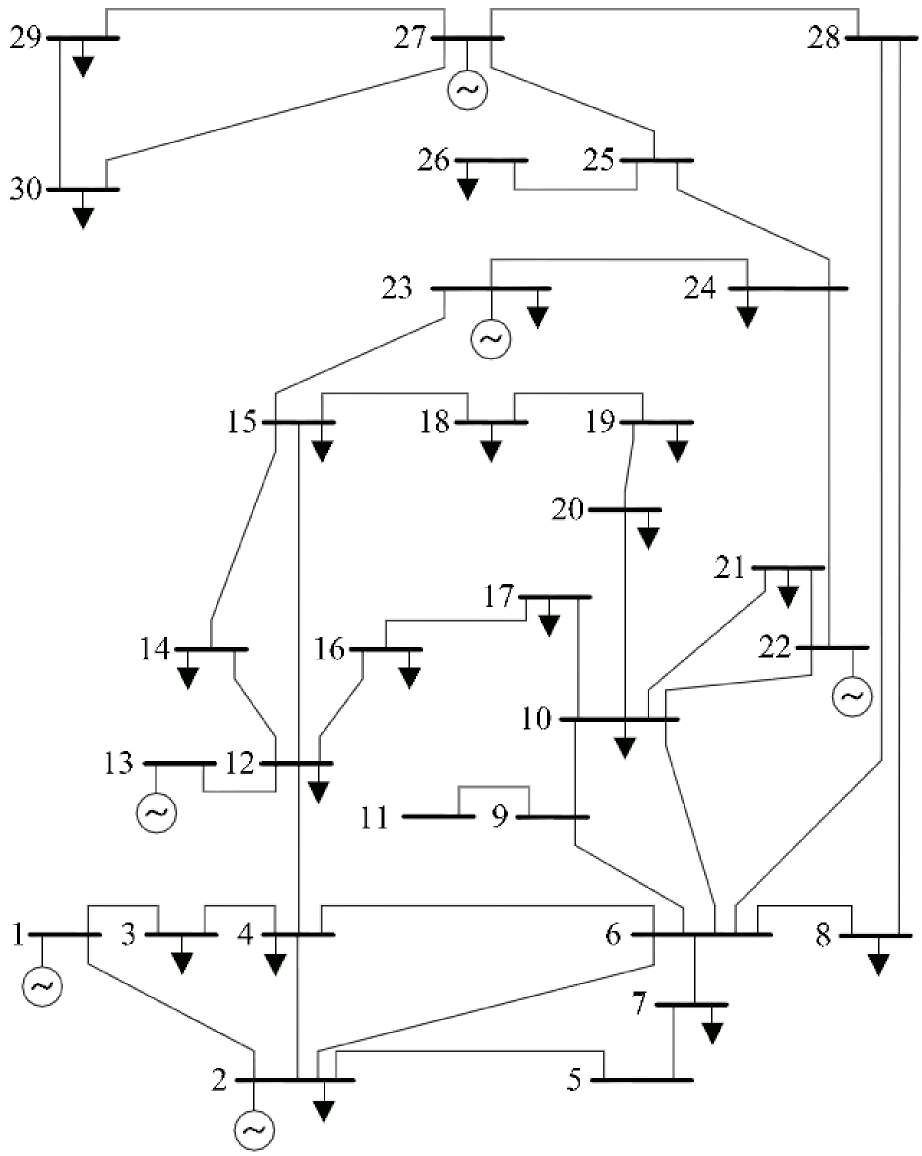

Figure 3-1 The IEEE 30 bus system (University of Washington, 1999)

Bus ID	Power	
	MW	**MVAR**
Bus 1	“0.0”	“0.0“
Bus 2	“21.7“	“12.7“
Bus 3	“2.4“	“1.2“
Bus 4	“7.6“	“1.6“

Bus 5	“94.2“	“19.0“
Bus 6	“0.0“	“0.0“
Bus 7	“22.8“	“22.8“
Bus 8	“30.0“	“30.0“
Bus 9	“0.0“	“0.0“
Bus 10	“5.8“	“5.8“
Bus 11	“0.0“	“0.0“
Bus 12	“11.2“	“11.2“
Bus 13	“0.0“	“0.0“
Bus 14	“6.2“	“6.2“
Bus 15	“8.2“	“8.2“
Bus 16	“3.5“	“3.5“
Bus 17	“9.0“	“9.0“
Bus 18	“3.2“	“3.2“
Bus 19	“9.5“	“9.5“
Bus 20	“2.2“	“2.2“
Bus 21	“17.5“	“17.5“
Bus 22	“0.0“	“0.0“
Bus 23	“3.2“	“3.2“
Bus 24	“8.7“	“8.7“
Bus 25	“0.0“	“0.0“
Bus 26	“3.5“	“3.5“
Bus 27	“0.0“	“0.0“
Bus 28	“0.0“	“0.0“
Bus 29	“2.4“	“2.4“
Bus 30	“10.6“	“10.6“

Table 3-1 The IEEE 30-bus test feeder bus load data (University of Washington, 1999)

3.3. The system modelling

The different levels of DG penetration considered as the gradual increase of renewable energy integration into the grid. In this thesis, the distributed generation considered as the energy mix generated from PV and wind plants. The DG penetration analysis starts at 15 %, then to 25-30%, and end with 50 % integration of DG with the grid. A conceptional system model given in the below figure 3-2. In the figure, S.G is the synchronous generator[8]and, it represents the current generation available in the network.

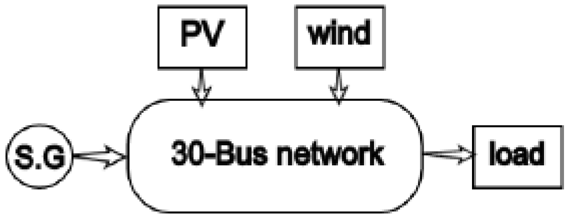

Figure 3-2 The conceptional system model

The different penetration levels have given in the below table 3-2, and the current generation available in the network will adjust according to the renewable input.

Penetration levels	**Total renewable contribution**
15 %	45 MW
25 %	75 MW
30 %	90 MW
50 %	150 MW

Table 3-2 The power generation from the renewables in MW

The individual renewable penetration contribution has taken according to the UK renewable market situations. Since in the UK, the wind is the major renewable resource compared with PV generation (UK government statistical press release, 2018), the analysis handled with strong wind penetration levels in the overall DG contribution levels. The Individual contribution levels given in the below table 3-3.

Penetration levels	**Individual DG contributions**
15 %	10 % wind and 5 % PV
25 %	20 % wind and 5 % PV
30 %	20 % wind and 10 % PV
50 %	40 % wind and 10 % PV

Table 3-3 The individual DG contributions for the models

3.3.1. Software used - 'ETAP'

The ETAP ("Electrical Transient and Analysis Program") is an electrical power system analysis software, which is used widely by different companies in worldwide for

[8] Synchronous generators are the majority source of commercial electrical energy.

industry and utility power system related analysis. It specialized in “the analysis, simulation, monitoring, control, optimization, and automation of electrical power systems” (etap, 2018). The renewable energy module in the software enables detailed power system analysis in “the calculations for accurate simulation, predictive analysis, equipment sizing, and field verification of wind parks, solar farms and other renewable distributed energy resources” (etap, 2018). The renewable integration and its impacts on the power system network can be analysed efficiently by using the different features available in the software. In this thesis, the impacts on the 33 kV distribution buses at the IEEE 30 bus test feeder due to PV and wind renewables integration is analysed using the ETAP. The impacts on voltage, short circuit current due to a fault, frequency, and harmonic effects at the buses evaluated by using load flow analysis, short circuit current analysis, transient stability analysis, and harmonic analysis, respectively.

3.3.2. The wind farm modelling

To model the wind turbine plant, the turbines of 2 MW rated capacity from one of the largest wind turbine manufacturing company, Vestas is picked. The selected type is ‘V110-2.0’. The technical specifications (Vestas, 2018) of this wind turbine are; the cut-in speed of this type is 3 m/s, and cut-out speed is 20 m/s. Hence, the wind turbine used for the power generation between these speeds (as in figure 2-7). It has the rotor diameter of 110m, and hub height is available in the range of 80m - 125m. The generator used in the model is a doubly fed induction generator (the type 3, which explained in section 2.2.2). The doubly fed induction generator is most preferable as these are variable speed types to utilize the maximum wind potential and generate higher output compared with the fixed speed type generators. The other advantages of this types are wider speed range operations, and a larger control of the output power in the circuit by the separate control of both active[9]and reactive[10]powers (Camm, et al., 2009). Therefore, the most popular double-fed induction generator selected for the wind turbines.

Here, in the model, by using this wind turbine a wind farm is designed. There are five, 2 MW wind turbines used, and the typical arrangement of the wind farm shown in the figure 3-3. This wind farm connected to 33 kV distribution bus by using a typical transformer rating of 0.69/33 kV, 15 MVA (SIEMENS, 2009). The typical values as per IEC standards have

9 Active power is the real power which is transferred to the load (Robbins & Miller, 2013)
10 Reactive power is the power oscillates back and forth between source and load (Robbins & Miller, 2013)

chosen for all other parameters that require to model and perform the various analysis (etap, 2018).

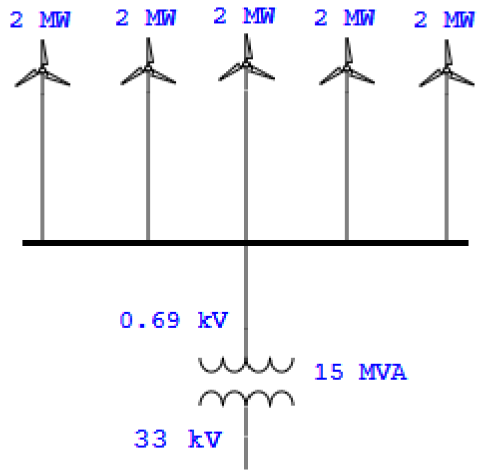

Figure 3-3 Typical arrangement of a wind farm

3.3.3. The PV farm modelling

In this thesis, the solar PV of total capacity 5 MW designed for the solar farm modelling. The 5 MW PV farm consists of five PV arrays with each has a rating of 1 MW. The selected PV array (Manufacturer: Q. CELLS) is of a poly-crystalline type with a nominal power rating of 230Wp[11]per panels. Each of the five PV arrays consists of 4320 solar panels and the panels arranged in the series-parallel combination. The total output voltage (DC) from the PV system is approximately 0.47 kV. An inverter with MPPT of rating 1.2 MW is connected at the output of each PV arrays to convert the DC output of the PV to AC before integrating into the grid. As explained in the section 2.3.1, the inverter with the maximum power point tracking (MPPT) helps for better solar energy extracting and to produce maximum possible power. Like in the wind farm, the output from the solar farm is connected to 33 kV distribution bus by using a step-up transformer of rating 0.48/33 kV, 6 MVA. A typical arrangement of PV panel used in this model given in figure 3-4. The other parameters are chosen as typical values as per IEC standards to perform various studies and to analyse the impact of DG penetrations.

[11] Nominal watt peak capacity under standard test conditions (Fong & Tippet, 2013)

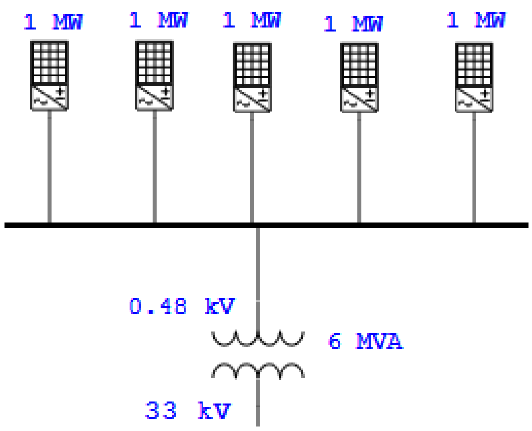

Figure 3-4 Typical arrangement of a PV farm

3.4. The tests performed

This section includes various analysis conducted to study the effect of DG integration into the grid. In this thesis, mainly four different tests are performed, and the analysis is done based on those tests. The test conducted with the help of ETAP software are:

- Load flow analysis
- Short-circuit fault analysis
- Frequency deviation analysis
- Harmonic Analysis

Each of these tests are explained below in detail.

3.4.1. Load flow analysis

The load flow analysis is essential when designing a new electrical power network or planning for the extension of an already existing power system in case of increased load demand (Wadhwa, 2009). The load flow solution gives the nodal (bus) voltages and phase angles, and hence, the power injection on all buses as well as the power flow through the network elements. Thus, the load flow analysis reflects the overall performance of the power network and the total power flow in the network under specified system constraints. The most important paraments in the load flow study are the “active and reactive power, and bus voltage magnitude and its phase angle” (Wadhwa, 2009). Normally, in the load flow study, for a given type of bus two out of the four quantities are defined, and the remaining two determined through the various techniques available for the load flow analysis (Jena, et al., 2018). Depending on the quantities have been specified, the buses are classified into, “load bus, generator bus, and slack bus” (Wadhwa, 2009).

a) Load bus (Wadhwa, 2009)

At this bus, out of the four parameters, the "active and reactive power specified" and it is necessary to "find the voltage magnitude and phase angle" through the load flow solution.

Example: Bus 14 in the single line diagram shown in figure 3-1

b) Generator bus (Wadhwa, 2009)

Here, the “active power” corresponding to the generator rating and the “voltage magnitude” corresponding to the generated voltage mentioned. Then, the “reactive power” generated, and the “phase angle of the bus voltage” is determined by using the load flow techniques.

Example: Bus 2 in the single line diagram shown in figure 3-1

c) Slack bus (Wadhwa, 2009)

The slack bus is the “reference or swing bus” in the power network. In general, the generator with the highest capacity connected to it is taken as the slack bus. Here, the “bus voltage magnitude and phase angle” are specified, and then, “real and reactive power” needs to calculate.

Example: Bus 1 in the single line diagram shown in figure 3-1

As the load flow equations are nonlinear and complex, the load flow studies performed by using the iterative methods. Some of the load flow analysis generally used are “1- Gauss Siedel method, 2- Newton Raphson method, 3- Fast Decoupled method, and 4- Decoupled method” (Jena, et al., 2018). In general, the second method, Newton Raphson is more preferred because of the greater accuracy, and faster convergence (Jena, et al., 2018). Therefore, in this thesis, the load flow analysis is performed by using the Newton Raphson method. The load flow analysis performed after each level of increase in the DG as in table 3-3. Later, the changes in the bus voltage compared with the original non-DG network is analysed and verified the changes are within the recommended limit as per the UK electrical regulations. Any changes beyond the recommended limit might causes problems in the power network as explained in the section 2.5.1. Here, the load flow analysis performed with the help of ETAP, and the load flow equation (Wadhwa, 2009) used to solve the equation is,

$$\begin{bmatrix} \Delta \mathrm{P} \\ \Delta \mathrm{Q} \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta \mathrm{V} \end{bmatrix}$$

Where, $J_1 = \frac{\partial \mathrm{P}}{\partial \theta}$; $J_2 = \frac{\partial \mathrm{P}}{\partial \mathrm{V}}$; $J_3 = \frac{\partial \mathrm{Q}}{\partial \theta}$; $J_4 = \frac{\partial \mathrm{Q}}{\partial \mathrm{V}}$

Here, "ΔP and ΔQ are bus real power and reactive power mismatch vectors between specified value and calculated value; $\nabla\theta$ and ΔV are bus voltage magnitude and angle vectors in an incremental form, and J_1 through J_4 are called Jacobian matrices" (Wadhwa, 2009).

3.4.2. Short-circuit current flow analysis

One of the major concerns of integrating DG into the power network is the change in magnitude and the direction of the fault currents. The large changes from the expected fault level currents might introduce a lot of issues in the power network as explained in the section 2.5.3.

In an electrical network, fault means the abnormal condition that causes disturbances in the network in the form of failure of the pieces of equipment used in the network. In general, the fault divided as the open circuit and short circuit fault (Tleis, 2008). The open circuit fault occurs because of the failure of joints on cables or overhead lines or due to the failure of a circuit breaker. For instance, two phases of the circuit breaker may properly open but the third one stuck in the closed position results in the open circuit fault (Tleis, 2008). The short circuit fault is mainly due to the weather-related issues. Some of the weather factors that lead to the short circuit are lightning, accumulation of snow or ice on the transmission line or strong wind or floods/fires beneath the overhead transmission line. The short-circuit fault may also be caused by human error during the maintenance time (Tleis, 2008). The most common faults are the short circuit faults and categorized (Wadhwa, 2009) as "single line to ground fault"; "double line to ground fault"; "line to line fault"; and "three-phase fault". Some of the typical short circuit faults are given in figure 3-5 to figure 3-7.

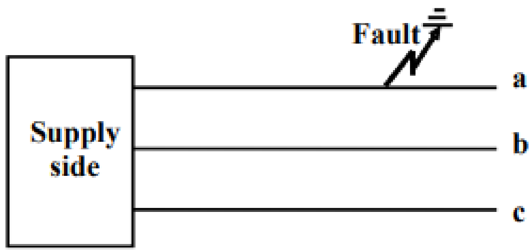

Figure 3-5 Typical "single line to ground fault" (Tleis, 2008)

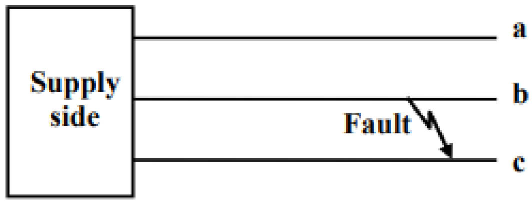

Figure 3-6 Typical "line to line fault" (Tleis, 2008)

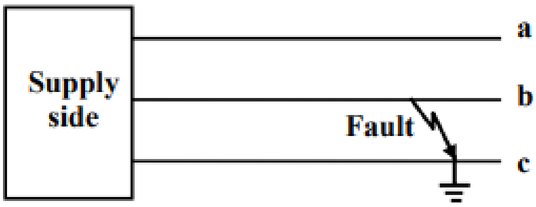

Figure 3-7 Typical “double to ground fault” (Tleis, 2008)

The above faults called unsymmetrical fault as it results in unsymmetrical fault current with change in magnitude and phase displacements at each of the transmission line conductors (a, b, and c in the figure 3-5 to figure 3-7) (Wadhwa, 2009). These are also called unbalanced fault as it results in an unbalanced current in the system. The most common type among these faults is the single line to ground fault. The other type of short-circuit fault is the three-phase fault. It is named as a symmetrical fault as the system remain balanced after the fault. Hence, it also called balance fault, and the two different possibilities of this fault have shown in the figure 3-8. However, the balanced fault is the most severe fault and it produces major problems in the power system (Wadhwa, 2009).

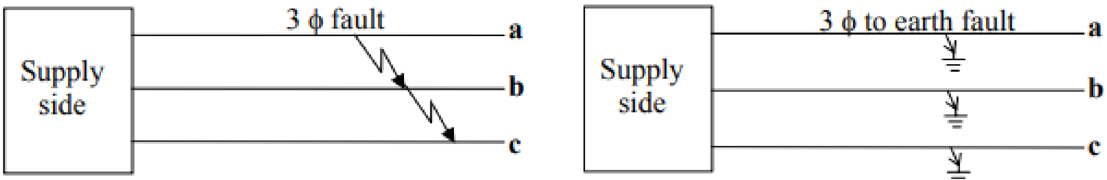

Figure 3-8 Three phase fault possibilities (Tleis, 2008)

The unsymmetrical fault current calculation is complicated as it required to solve an unbalanced 3- phase complex circuit. As the direct solution of such a circuit is very difficult, the solution more easily calculated by using the symmetrical components (Wadhwa, 2009).

In this thesis, the faults introduced at few buses in the IEEE 30 bus distribution network, and then, analysed the changes in the short circuit current resulted compared with the original network for each of the distribution levels as explained in table 3-3. Since the standard followed to calculate the short circuit current in the UK is IEC 60909 standard, the calculation is done based on the same standard. The IEC 60909 classify the short circuit current according to their maximum or minimum magnitudes and fault distance from the generator locations. In general, the equipment settings are done based on the maximum short-circuit current, and minimum currents used for the protective device settings (Sweeting, 2011).

In this thesis, as per the IEC standard, the parameter "initial symmetrical short circuit current" is used to compare the short circuit fault level for each of the DG penetration levels. The "initial symmetrical short circuit current is defined as the r.m.s value of the ac symmetrical component of a prospective (available) short-circuit current applicable at the instant of the short-circuit" (Sweeting, 2011). The "prospective (available) short-circuit current is the current that would flow if the short-circuit replaced by an ideal connection of negligible impedance without any change of the supply" (Sweeting, 2011).

The "initial symmetrical short circuit current" is calculated by using the below equation (Sweeting, 2011):

$$I''_k = \frac{c\, U_n}{\sqrt{3} Z_k}$$

Where

I''_k– Initial symmetrical short circuit current(rms)
U_n– Nominal voltage (33kV here)
c – voltage factor; for maximum current calculation, it has taken as 1.1 at 33kV.
Z_k – The resulted equivalent impedance due to the fault.

3.4.3. Transient stability analysis (Frequency deviations)

"The transient analysis intended to understand the system dynamic responses and stability boundaries of a power system before, during, and after system changes or disturbances" (Chang, et al., 1995). Generally, this technique used by the power system planning and operating engineers, and important changes or conclusions or decisions are made based on such analysis. The disturbances usually considered are "the generator outages, short-circuits caused by lightning or other fault conditions, sudden large load changes, small random fluctuations in load demands etc." (Chang, et al., 1995). In a power network, it is necessary that the system needs to go back to the initial steady-state condition of operation after being subjected to a small disturbance. Such systems are called steady-state stable systems (Kundur, et al., 2004). However, in some cases, "especially under large disturbances, a system might reach a new acceptable steady-state condition that is different from the original steady-state condition". Such systems are called "transiently stable systems" (Kundur, et al., 2004). In general, the power system stability is divided into "rotor angle stability, frequency stability, and voltage stability" (Refaat, et al., 2017).

The rotor angle stability is the ability of the synchronous machine of an interconnected power system to remain in the same state as in the initial state following a disturbance from the initial operating conditions. The frequency stability refers to maintain a steady frequency following a large disturbance, and the voltage stability is referring to the ability to maintain the same steady state voltage at all buses in the system after being exposed to a disturbance (Refaat, et al., 2017).

As detailed in table 3.2, the power generated from the renewables helps to decrease the power generation from the conventional power units. Electrical network with large DG penetration and a large disturbance within such systems may cause uncertainty on the power system stability. For instance, the disturbances such as the outage of the tripping of large DG units due to anti-islanding protection. Such a high percentage of the tripping of DG will result in the frequency deviations (Seneviratne & Ozansoy, 2016). In addition, an ordinary designed PV and wind technologies lack the inertia support, and it could lead to a difference in the frequency. The high level of DG penetration will decrease overall system inertia[12]and it will increase the frequency fluctuations (Seneviratne & Ozansoy, 2016). The frequency deviation is based on the below equation,

$$P_g - P_l = \frac{d}{dt}\left(\frac{1}{2}J_{System}.\omega_{el}\right)$$

Where

P_g – The generated power
P_l – Load power
J_{System} – The system inertia.
ω_{el} – The angular frequency.

In this thesis, the transient stability analysis done during the power outage of renewable generation, that is when both PV and wind are not able to generate any electricity. There are possibilities to lose the PV generation in case of extreme weather conditions as well as during the passage of a cloud. Unlike the changes in the position of the sun that affects the PV output approximately in a uniform fashion, the effect due to the clouds not driven by a similar uniform process, and it varies depending on the other parameters in the atmosphere. The clouds might cause wide “changes in PV output across the plants and between separate plants” (Berkeley lab, 2009). By considering these conditions, the stability analysis based on such an event modelled here. Similarly, in the case of wind, the stoppage of wind generation is based on the consideration of under extreme weather condition. In the case of a heavy wind speed, that is above the cut-out speed of 20 m/s, for the selected model (Vestas ‘V110-2.0’) in the system, the break is employed on the rotor to push them to stop

[12] The “system inertia is described as the opposing forces on an object to change its motion, either at rest or when moving” (Seneviratne & Ozansoy, 2016)

the electricity production due to the protection requirements. Likewise, for any speed below 3 m/s, the chosen model is unable to generate any electricity. Therefore, these situations modelled as sudden loss of PV and wind turbine. This analysis is executed on each level of DG penetration as indicated in table 3-3.

3.4.4. Harmonic analysis

The" harmonic analysis is used to quantify the distortion in voltage as well as current waveform" (IEEE PES, 1998), and to understand the existence of different individual harmonic components to design the suitable circuits for mitigating the problems that caused due to harmonics. As explained in the section 2.5.2, the presence of the power electronic converters in the distributed generation is one of the main reasons behind the power quality related problems. The presence of the power electronics components without a suitable harmonic filter can create a severe problem in the power network. In this thesis, the harmonics due to inverters that used in the PV system is modelled, studied and analysed the outcome according to the relevant standards.

To understand the harmonic effects due to the solar inverter on the bus, two different harmonic sources, a typical IEEE six-pulse current harmonic source, and a typical IEEE 12-pulse current harmonic source considered in the PV inverter of the ETAP solar farm model. The assumed waveform of these two harmonics has given in figure 3-10 and 3-11. The harmonics are generated due to the switching operation of the switches (S_1 to S_6) in the inverter circuit as shown in the figure 3-9.

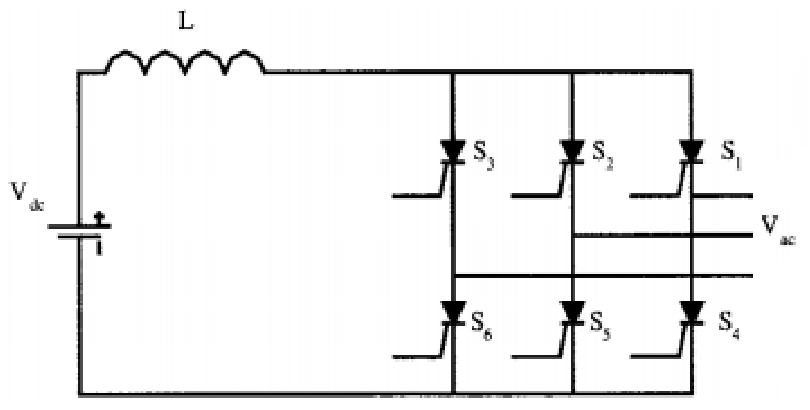

Figure 3-9 A typical basic current source inverter circuit (6- Pulse) (Bendre, et al., 2002)

Here, V_{dc} and V_{ac} are the input dc and output ac voltage respectively, and L is the inductor used (as a storage element). The switches, S_1 to S_6 shown in the figure are the thyristor switches and is turned on or off by using the pulses generated by different techniques such as pulse width modulation (PWM) techniques to generate a sinusoidal wave.

In general, a 12-pulse circuit designed by combining the two 6 pulse converter circuit shown in the figure 3-9. Normally, the harmonics resulted from the 12-pulse circuit and its effect on the fundamental wave is lesser compared with the 6 pulse circuits (Pietkiewicz & Biner, 2012).

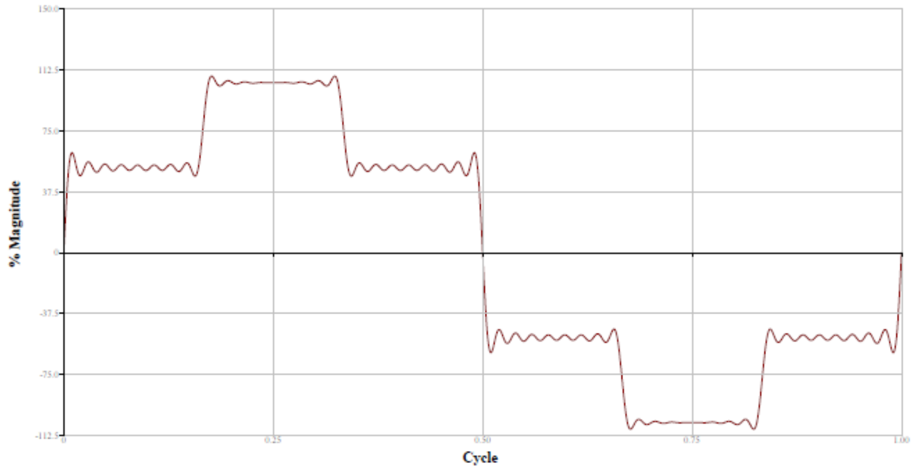

Figure 3-10 Typical IEEE 6 pulse current harmonic source (etap, 2018)

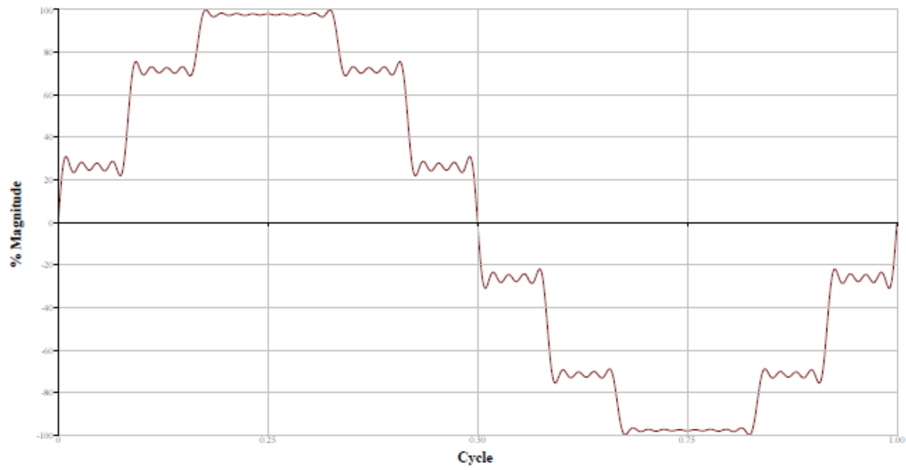

Figure 3-11 Typical IEEE 12 pulse current harmonic source (etap, 2018)

3.5. The Scenarios

As explained in the above section, the total distributed generation that penetrated to the IEEE 30 bus network have based on the number of wind and PV farms connected to the system. The two types of farms that contributed to the distributed generation are:

- The wind farm of total generation =10 MW (5X2MW)
- The solar PV farm of total generation = 5 MW(5X1MW)

The four different scenarios adapted to analyse the impacts of distributed generation into the grid. It based on the penetration level as explained in table 3-3. To accomplish the intended level of penetration, several farms linked to the bus. The selection of the buses to attach the PV and wind farms are based on the high-level analysis to reduce the impacts on the grid buses as possible. The different scenarios considered here explained below.

3.5.1. Scenario 1: DG penetration level of 15 %

As the impacts on the grid due to the low levels of distributed integration are minimal, the first scenario considered in this thesis is 15 % of DG penetration. To achieve the 15% of penetration level (10% wind and 5% PV), three 10 MW wind and three 5 MW PV farms integrated with selected IEEE 30 test feeder network system.

3.5.2. Scenario 2: DG penetration level of 25 %

In the scenario 2, the DG penetration level considered is 25%. It achieved through the integration of six wind farms and three PV farms.

3.5.3. Scenario 3: DG penetration level of 30 %

In this case, six PV and a same number of wind farms are connected to the grid to accomplish the penetration level of 30 %.

3.5.4. Scenario 4: DG penetration level of 50 %

The highest distributed generation penetration considered for this thesis is 50 % of total generation capacity. Hence, in scenario 4, the 50 % of DG integration is achieved by connecting a total of 12 wind farms and 6 PV farms.

The tests those explained in section 3.4 are conducted for all the above scenarios, scenario 1 to scenario 4. The results of these tests compared with the original IEEE 30 bus test feeder outcome, that is, the network with no distributed sources are connected. Then, the next approach is to evaluate the results of the tests based on the relevant standards as well as the UK regulatory requirements. As explained in the above sections, since wind generation has been considering as the predominant source of renewable electricity generation in the UK, more wind farms connected to the grid compared with the PV farms. Therefore, in scenario 1 and scenario 3, 67 % of distributed generation is considered from the wind sources. Likewise, in scenario 2 and 4, 80 % of it from the wind farms.

The below table 3-4 describes a short summary of the all scenarios that considered in this dissertation.

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total DG %	15 %	25 %	30 %	50 %
Wind %	10 %	20 %	20 %	40 %
PV %	5 %	5 %	10 %	10 %
Total DG in MW	45	75	90	150
Number of 10 MW wind farms	3	6	6	12
Number of 5 MW PV farms	3	3	6	6
Conventional generation in MW	255	225	210	150

Table 3-4 The summary of DG integration scenarios

3.6. Summary

This chapter described the representative distribution network, and the software used to model the distributed generation. Also, detailed the parameters and techniques adopted to build the distributed sources. Then, listed the various studies that are used to identify the challenges that resulted because of the DG integration into the network. In the end, presented the different scenarios that framed to analyse such impacts. The DG integration studies started at a penetration level of 15 % of the total conventional generation available in the network and continued until it reaches 50%. According to the progress in the DG penetration, the conventional generation lessened. The outcome and the observations about the results presented in the succeeding chapter.

4. Simulation Results and Discussions

4.1. Introduction

This chapter demonstrates the various outcomes regards with the integration of DG into the distribution network. The tests performed on the IEEE 30 bus test feeder, and the results are shown here based on the simulations that executed by using the software ETAP. To assess the impacts of DG into the grid, the system without any DG connection taken as a reference for most of the cases. The simulation results and key learning outcomes explained in this chapter for the four scenarios as described in section 3.5. This chapter divided into 4 sections; the section 4.2 shows the outcomes from the load flow analysis regards with the voltage level changes, and section 4.3 explains the fault current fluctuations because of the DG integration. Later, section 4.4 illustrates the deviations in the frequency, and finally, section 4.5 shows the total harmonic distortion levels in all scenarios.

4.2. Load flow analysis

The IEEE 30 test feeder parameters that shown in table 3-1 and Appendix A are used to build the distribution network model as shown in figure 3-1. Then, it was necessary to make sure that the system is stable to start the analysis. Hence, the load flow analysis executed for the base model and analysed the voltage magnitudes, the phase angle of the voltage at each bus, and the real and reactive power flowing in each transmission line from the load flow report. The resulted load flow analysis report shown here based on the Newton-Raphson method as explained in the section 3.4.1. Later, similar load flow studies performed on different models. In this thesis, the variation on the voltage magnitude is only taken into accounts to study the DG integration issues. Therefore, the resulted voltage magnitude from the base network is taken as reference and then, investigated the variation from the reference magnitudes for all scenarios, from scenario 1 to scenario 4. The detailed load flow report of the test feeder network without any DG is given in Appendix B as a prototype.

- **Scenario 1 results**

For scenario 1, the system considered is a combination of 10 % of wind and 5 % of the PV distributed sources integration into the network. The table 3-4 explains more about the scenario 1. The buses that used to connect with the DG network for the scenario 1 given in the below table 4.1. The selection of the bus for the DG integration based on a high-level analysis to reduce the impact to a minimum level as possible by analysing the load flow results of the base network model.

Distributed sources	Bus connected
PV farm	26,29,30
Wind farm	15,21,30

Table 4-1 The DG connected buses for scenario-1

The voltage deviation percentages resulted from the load flow analysis of scenario 1 given in the below table 4-2. The buses those are coming under the UK distribution voltage levels shown here from the test feeder network. The maximum permitted variation as per the UK legislation is -6 % to +6 % for the distribution voltage levels (below 132 kV), and hence, the results are within this range.

Bus Id	Nominal kV	% of voltage deviation from the original network
9	33	0.74
10	33	1.18
12	33	0.77
14	33	1.21
15	33	1.81
16	33	0.97
17	33	1.11
18	33	1.6
19	33	1.48
20	33	1.41
21	33	1.73
22	33	1.67
23	33	1.84
24	33	1.86
25	33	2.13
26	33	3.2
27	33	1.82
29	33	3.67
30	33	4.73

Table 4-2 The scenario 1 voltage deviation %

- **Scenario 2 results**

The system considered in scenario 2 is a combination of 20 % of wind and 5 % of PV distributed system. The 10 % increase in the wind generation compared with the scenario 1 achieved by adding more wind farms to the buses, and all the buses with DG integration given in table 4.3. The more features regarding the PV and wind farms can be found on table 3-4. The buses with less voltage variation from the scenario 1 output are preferred to integrate with the new wind farms. The resulted in bus voltage variation after the load flow test of scenario 2 is given in table 4-4, and the voltage deviations are within the limit as per UK standards.

Distributed sources	**Bus connected**
PV farm	26,29,30
Wind farm	9, 15,16,20,21,30

Table 4-3 The DG connected buses for scenario-2

Bus Id	**Nominal kV**	**% of voltage deviation from the original network**
9	33	1.86
10	33	2.68
12	33	1.53
14	33	2.16
15	33	2.99
16	33	3.12
17	33	2.83
18	33	3.63
19	33	3.99
20	33	4.17
21	33	3.19
22	33	3.11
23	33	3.03
24	33	3.06
25	33	2.85
26	33	3.93
27	33	2.25

29	33	4.1
30	33	5.16

Table 4-4 The scenario 2 voltage deviation %

- **Scenario 3 results**

In scenario 3, a combination of 20 % of wind and 10 % of the PV distributed system provided. The 5 % increase in the PV generation compared with the previous scenario is achieved by adding more PV farms to the buses, and all the buses with DG connection given in table 4.5. Here also used the same techniques as described in the scenario 2 for selecting the new buses. The table 4-6 shows the resulted voltage deviations after load flow test of scenario 3. The more details about PV and wind farms can be found in table 3-4. The results show that the voltage deviation is within the permitted UK regulatory variation limits.

Distributed sources	**Bus connected**
PV farm	14,17,25,26,29,30
Wind farm	9,15,16,20,21,30

Table 4-5 The DG connected buses for scenario-3

Bus Id	**Nominal kV**	**% of voltage deviation from the original network**
9	33	1.9
10	33	2.72
12	33	1.59
14	33	2.57
15	33	3.11
16	33	3.23
17	33	2.97
18	33	3.72
19	33	4.07
20	33	4.23
21	33	3.24
22	33	3.17
23	33	3.17
24	33	3.23
25	33	3.24

26	33	4.32
27	33	2.34
29	33	4.2
30	33	5.25

Table 4-6 The scenario 3 voltage deviation %

- **Scenario 4 results**

In this last scenario, more wind farms added to the network and analysed the outcome. Here, the wind contribution is chosen as 40 % and the PV as 10 % to make the DG contribution at 50%. Six more wind farms added to the network compared with the scenario 3 to achieve 40 % of wind generation. Again, the technique used to select the new buses is the same as in the previous cases. The table 4-7 shows the DG connected buses, and table 4-8 gives the resulted voltage deviation after the load flow analysis of the scenario 4. The more details regarding the PV and wind contributions can be found in table 3-4. The results show that for most of the buses, the voltage deviation exceeded 6% limit as per the UK regulation.

Distributed sources	Bus connected
PV farm	14,17,25,26,29,30
Wind farm	9x3,12,14, 15,16,20,21x2,27,30

Table 4-7 The DG connected buses for scenario-4

Bus Id	Nominal kV	% of voltage deviation from the original network
9	33	4.03
10	33	5.39
12	33	4.37
14	33	6.9
15	33	6.27
16	33	5.97
17	33	5.67
18	33	6.72
19	33	6.97
20	33	7.07
21	33	6.45
22	33	6.32

23	33	6.38
24	33	6.46
25	33	6.52
26	33	7.63
27	33	5.65
29	33	7.52
30	33	8.58

Table 4-8 The scenario 4 voltage deviation %

4.2.1. Discussion on load flow analysis simulated results

The below graph 4-1 shows the summary of the voltage variations at all the 33kV distribution buses of IEEE 30 bus test feeder network.

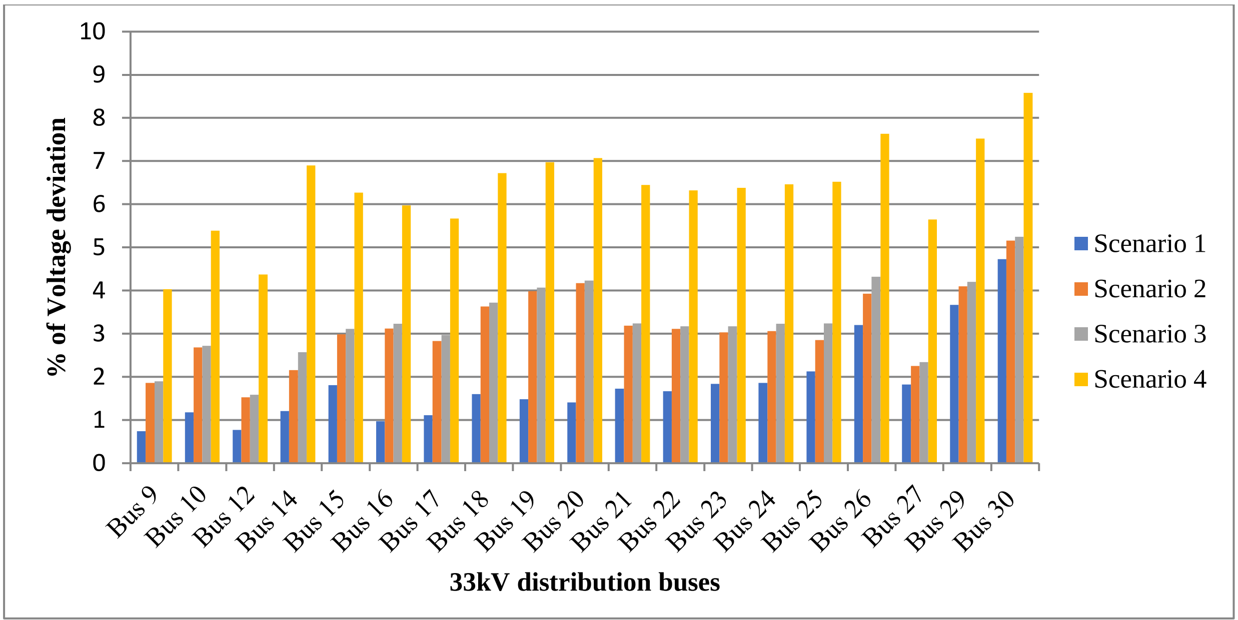

Figure 4-1 Summary of voltage deviation % at the distribution buses for all the scenarios

The above figure shows that any DG integration up to 30% (scenario 3) is acceptable as the voltage magnitude deviation is within the limit (6%) as per the UK legislation. For scenario 3, at the bus 30, the voltage magnitude variation is over 5%, and it is close to the upper 6% voltage limit. Hence, more penetration of DG into the network may not possible. In the case of scenario 4, that is when the DG is 50%, for all the buses except 9,10,12,16,17, and 27 the voltage deviation is above 6 %. It is notable that the voltage fluctuations are not only affected for the DG integrated buses but also in the neighbouring buses as well, and it may lead to several problems as explained in the section 2.5.1. The variations are high for the other parameters such as voltage phase angle and power flows. The voltage magnitude variation is mainly due to the changes in the power flow resulted because of the introduction of the DG into the network as explained in the literature reviews section. Therefore, it can conclude that any DG integration above 30% requires extensive study and planning to make sure that changes in voltage magnitude are within the acceptable limits by proper control of the power flows in the network.

4.3. Short circuit fault level analysis

To understand the changes in the short fault circuit current level, few faults introduced at some distribution buses of the IEEE 30 bus test feeder. To understand the changes, initially at the original test feeder network, the faults included at the buses 30,29,19, and 15, and then, calculated the resulted current. Again, the same faults at the same buses as in the original test feeder introduced for all the scenarios, from scenario 1 to scenario 4. Later, the output fault current compared with the reference fault current, that is, fault current from the original test feeder without any DG. The DGs are connected to the same bus as described in the load flow analysis section 4.2 for each scenario (Table 4-1, 4-3,4-5, and 4-7). The fault currents calculated by using the IEC 60909 specifications as per the recommended UK regulatory frame. Therefore, in this thesis, the fault currents used to evaluate the outcome from each of the scenarios is the “initial symmetrical short circuit current” as per IEC 60909. The more details about these given in the section 3.4.2. The selection of buses to inject the fault based on the location, type, and the number of DG’s connected to the buses. The main features of the selected buses are: in the case of bus 30, it is appearing after a long distribution feeder and is away from the central complex interconnected network. Therefore, both PV and wind plants connected to it. There are several other distribution buses are connected to the distribution bus 19, and hence, no DG is selected to connect with it to lessen the influence on other buses. The bus 29 is also apart from the central complex interconnected network, and only a PV farm connected to it. Likewise, for the bus 15, only a wind farm integrated with it.

- **Scenario 1 results**

The initial symmetrical short-circuit current resulted at the buses because of the introduction of faults at the buses 15,19,29, and 30 in case of 15% of DG penetration into the test feeder network given in the below table 4-9. The fault currents due to the occurrence of the same faults at the base network without any DG is also given in the table to compare the changes in the fault level currents. The table shows the fault current is increased at each of the buses due to the introduction of the DG and can see that the line to ground fault resulted in more deviations from the base network compared with the other faults.

Faulted buses	3-phase fault levels		Line to ground (LG) fault levels		Line to line (LL) fault levels		Double line (LLG) to ground fault levels	
	Base model	**Scenario 1**	**Base model**	**Scenario 1**	**Base model**	**Scenario 1**	**Base model**	**Scenario 1**
Bus 15	13.08	14.17	11.94	14.372	11.34	12.28	12.68	14.5
Bus 19	9.16	9.361	8.32	8.857	7.94	8.11	8.82	9.21
Bus 29	4.08	4.518	3.8	5.08	3.53	3.91	3.98	4.97
Bus 30	4.28	5.366	3.75	6.27	3.71	4.65	4.15	6.16

Table 4-9 The symmetrical short-circuit current(kA) at the faulted bus for scenario 1 & base case

- **Scenario 2 results**

The symmetrical short-circuit current of faulted buses in case of base network and 25% of DG integration into the grid given in table 4-10. The results show some increase in the fault levels compared with scenario 1.

Faulted buses	3-phase fault levels		LG fault levels		LL fault levels		LLG fault levels	
	Base model	**Scenario 2**	**Base model**	**Scenario 2**	**Base model**	**Scenario 2**	**Base model**	**Scenario 2**
Bus 15	13.08	14.575	11.94	15.098	11.34	12.629	12.68	14.993
Bus 19	9.16	10.11	8.32	10.294	7.94	8.756	8.82	10.217
Bus 29	4.08	4.522	3.8	5.084	3.53	3.916	3.98	4.976
Bus 30	4.28	5.37	3.75	6.274	3.71	4.648	4.15	6.159

Table 4-10 The symmetrical short-circuit current(kA) at the faulted bus for scenario 2 & base case

- **Scenario 3 results**

The 30 % of DG integration resulted in the below symmetrical short-circuit current as shown in table 4-11 at the faulted buses. As in the scenario 2, the fault level current again increased when integrating more DGs.

Faulted buses	3-phase fault levels		LG fault levels		LL fault levels		LLG fault levels	
	Base model	**Scenario 3**	**Base model**	**Scenario 3**	**Base model**	**Scenario 3**	**Base model**	**Scenario 3**
Bus 15	13.08	14.572	11.94	15.388	11.34	12.627	12.68	15.145

Bus 19	9.16	10.104	8.32	10.334	7.94	8.75	8.82	10.25
Bus 29	4.08	4.523	3.8	5.096	3.53	3.917	3.98	4.984
Bus 30	4.28	5.369	3.75	6.282	3.71	4.648	4.15	6.165

Table 4-11 The symmetrical short-circuit current(kA) at the faulted bus for scenario 3 & base case

- **Scenario 4 results**

The 50% of DG integration produced the symmetrical short-circuit current at the faulted buses as shown in table 4-12. The results show a large jump in the fault level currents compared with the base scenario.

Faulted buses	3-phase fault levels		LG fault levels		LL fault levels		LLG fault levels	
	Base model	Scenario 4	Base model	Scenario 4	Base model	Scenario 4	Base model	Scenario 4
Bus 15	13.08	15.561	11.94	16.819	11.34	13.48	12.68	16.3
Bus 19	9.16	10.325	8.32	10.596	7.94	8.941	8.82	10.525
Bus 29	4.08	4.692	3.8	5.301	3.53	4.063	3.98	5.167
Bus 30	4.28	5.528	3.75	6.468	3.71	4.785	4.15	6.334

Table 4-12 The symmetrical short-circuit current(kA) at the faulted bus for scenario 4 & base case

4.3.1. Discussion on short-circuit fault level analysis simulated results

The below figures from 4-2 to 4-4 shows the summary of the resulted initial symmetrical short-circuit current at the faulted buses. By analysing the figures, it can conclude that as the percentage of the DG integration increases the short-circuit current levels at the faulted buses also increased for all the cases. It is mainly due to the change in the resulted equivalent impedance at the fault location as explained in the section 3.4.2. In addition, it exposes that the DG integration is adversely affected on the most common single line to ground fault as it resulted in higher changes in the fault current compared with the original network for all the scenarios

The table 4-13 illustrates the percentage of change in the fault current in scenario 4, where 50% of DG integrated into the grid from the base scenario, where the DG integration is 0%. It calculated by using the below equation:

$$\frac{Scenario\ 4's\ fault\ current - Base\ case\ fault\ current}{Base\ case\ fault\ current}$$

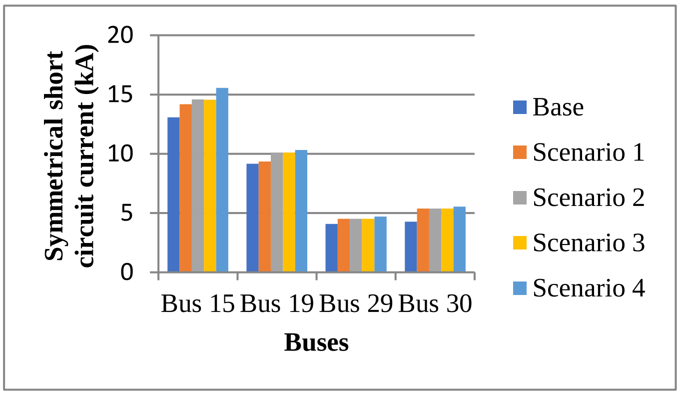

Figure 4-4 Summary of 3-phase faults at the faulted buses

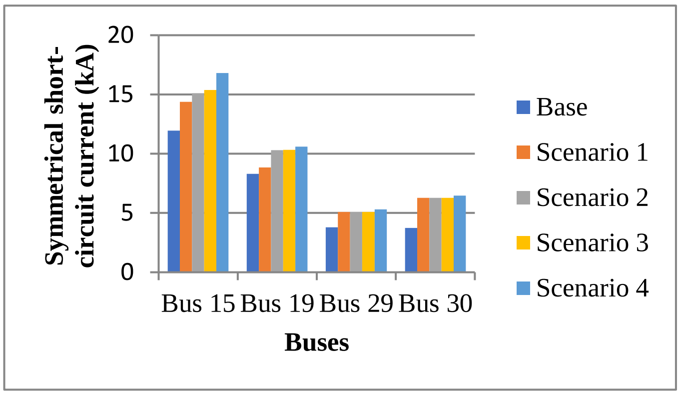

Figure 4-3 Summary of LG faults at the faulted buses

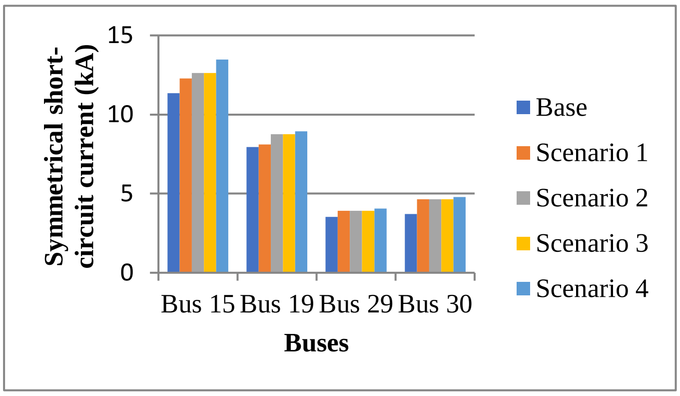

Figure 4-2 Summary of LL faults at the faulted buses

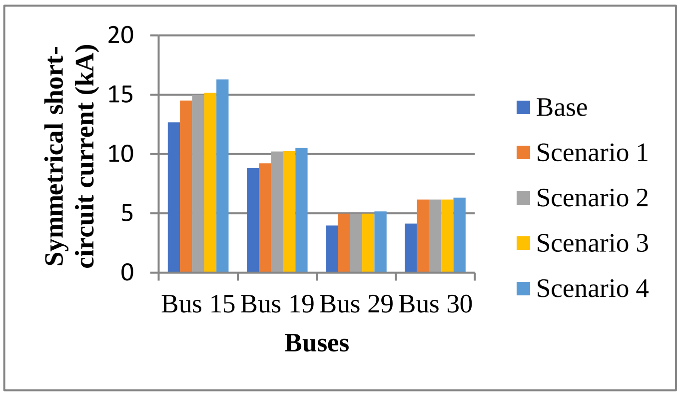

Figure 4-5 Summary of LLG faults at the faulted buses

Name of the fault	**% of changes in the fault current from the base case (with no DG) to the 50 % of DG integration(Scenario 4) into the grid**			
	Bus 15 (Wind farm connected)	**Bus 19 (No DG connected)**	**Bus 29 (PV farm connected)**	**Bus 30 (with both PV & Wind farm)**
Three-phase fault	18.9%	12.7%	15%	29.1%
Line to ground fault	40.8%	27.4%	39.5%	72.4%
Line to line fault	18.8%	12.7%	14.9%	29.0%
Double line to ground fault	28.5%	19.3%	29.9%	52.7%

Table 4-13 The % of changes in the scenario 4's fault current with respect to the base case (no DG's)

From the table 4-13, it noted that bus with both PV and wind farm connected (bus 30) produced a large increase in the fault current while the bus with no DG connected (bus 19) resulted in fewer changes. Also, the results shown from the table illustrate that wind farms connected bus has higher changes in the fault levels compared with PV farms except for the LLG fault as the wind farm capacity (10 MW) is higher compared with the PV farm (5 MW). In an electrical network, the fault current level is a critical parameter that needed to be pre-calculated at every common point in the grid for the protection as well as the sizing of the electrical installations. It is noticeable that for all scenario's, the fault current level increased at the faulted buses. Therefore, proactive measures need to take to avoid the adverse effects due to the increased fault levels. In the case of a large increase in fault level (scenario 4 in this thesis), all the types equipment and protection devices that designed based on the conventional power network need to redesign in accordance with the DG penetration. The fault level depends on the location, type, and size of the DG. Hence, considering all the above cases, a thorough analysis is necessary before integrating any DG penetration close to 30 % as the changes in the fault level for all types of fault are very big. The existing network parameters will also be affected by the increased fault level as explained in section 2.5.4. Therefore, the integration without proper analysis may lead to blackouts or expensive maintenance on the system components.

4.4. Frequency deviation analysis

The changes in the frequency due to the DG integration assessed through the transient stability analysis. It normally determined by assuming some possible real-time events at a specified time, and then, analysed its effect on the stability of the network. Thus, the transient stability analysis helps to thoroughly investigate the behaviour of the system under various conditions. In this thesis, to study the stability in terms of frequency, the event is assumed as 'generation from DG's is zero at a specified time'. Then, analysed the effects due to this action on the grid for all the scenarios. In real time, there are occasions when PV's are not able to generate power such as during the cloud passage time and at nights; in case of wind farms, power production halts when the speed is beyond the speed limits (cut-in and cut-out speeds). As per the UK legislative requirements, the frequency deviation always should be within the 1% limits from the standard frequency. This condition is checked during and after the occurrence of the assumed event for all the scenarios. The DGs are connected to the same bus as described in the load flow analysis section 4.2 for each scenario (Table 4-1, 4-3,4-5, and 4-7).

- **Scenario 1 results**

In the case of 15 % DG integration, the event assumed as both PV and wind plants are not able to generate any electricity at the 30th second. The resulted frequency curve is given in the below figure 4-6. The frequency deviation characteristics are almost the same for all the buses, and therefore, graphs for some buses only shown below. The resulted in deviations are within the -1% to 1 % UK legislative limit.

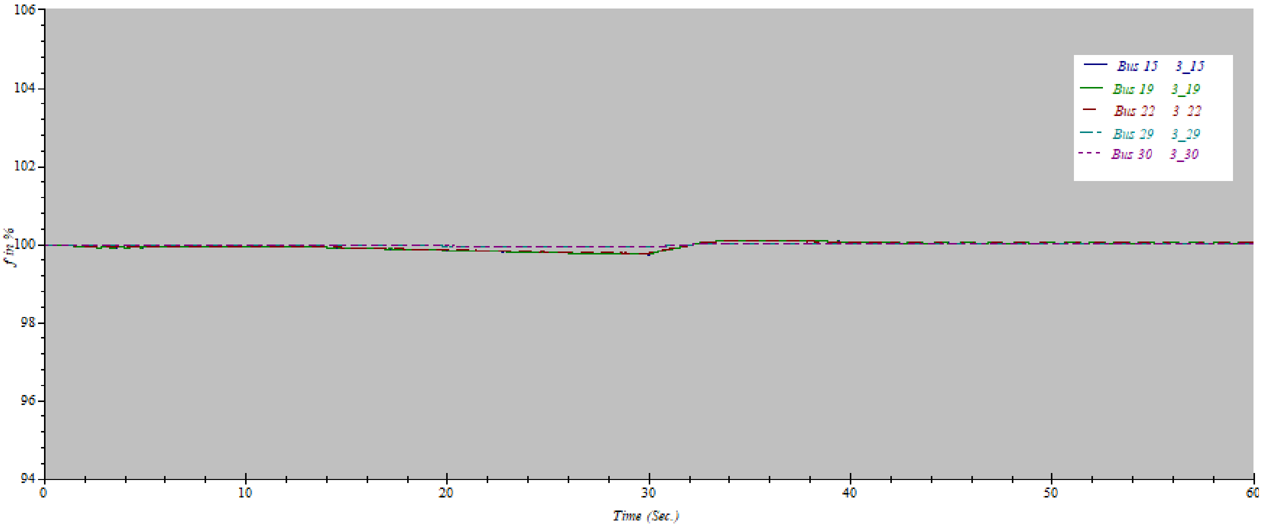

Figure 4-6 The frequency deviation at the buses for scenario 1 during the DG loss

- **Scenario 2 results**

In this case, the event assumed as all 25% of the DG production is lost at the 30th second. It ended in a frequency deviation curve as shown in the figure 4-7. The frequency deviation characteristics are similar for all the buses, and hence, shown curves for some of the buses. The slight deviations between the curves are due to the difference in the distance of the buses to the DG as well as the generator location. However, all the bus deviations are within -0.5% to +0.5% limit.

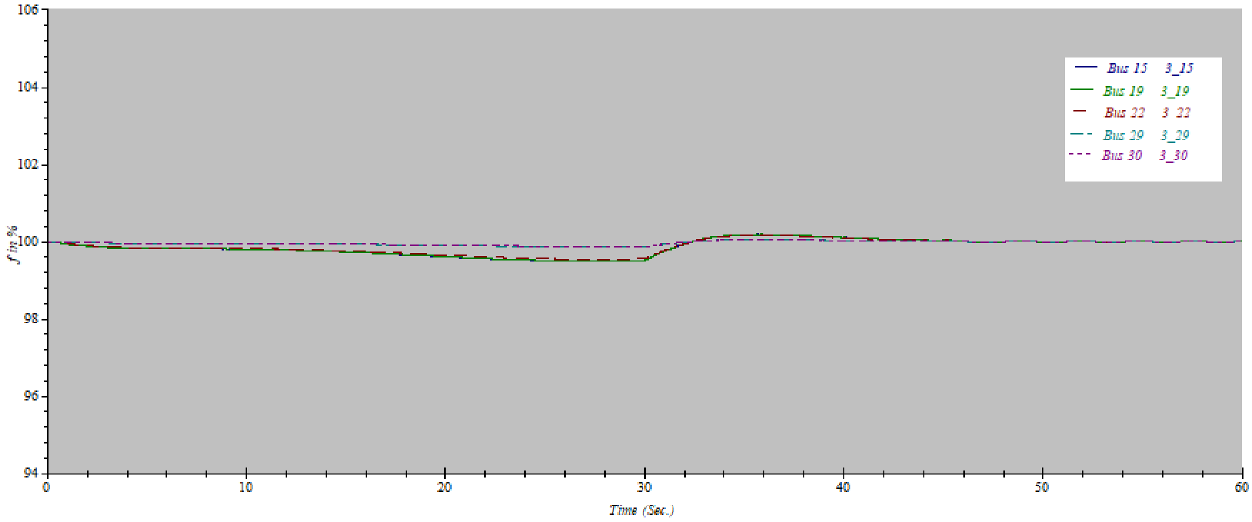

Figure 4-7 The frequency deviation at the buses for scenario 2 during the DG loss

- **Scenario 3 results**

The 30 % of DG loss at 30th second resulted in the below stability curve as shown in the figure 4-8. As in other cases, since the resulted frequency deviations are the same for all the buses, the curve at some of the buses is shown below. The results show that all the frequency deviations are within the UK legislative recommended limit.

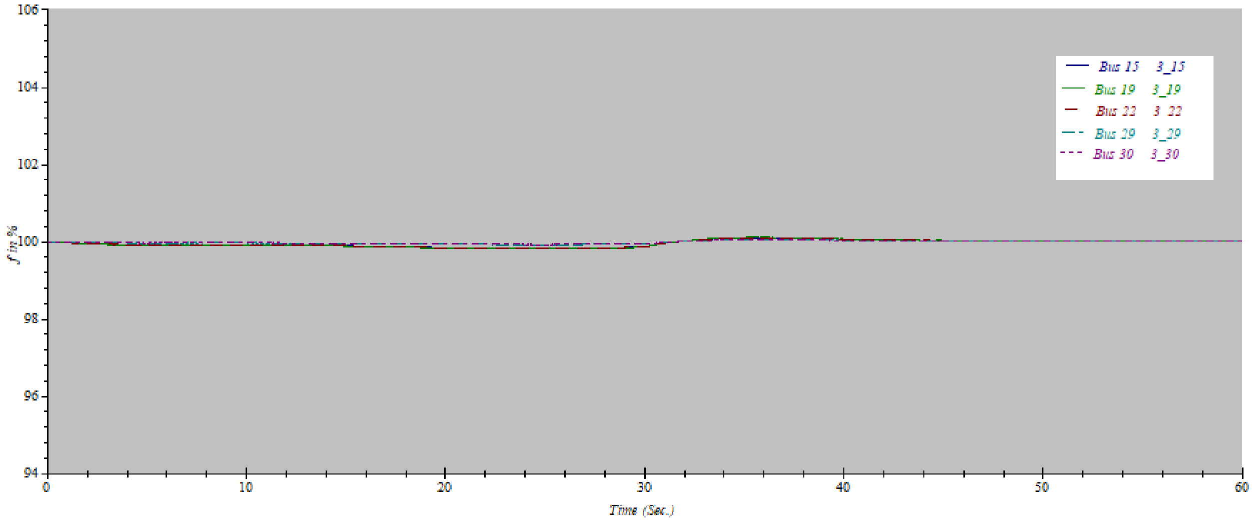

Figure 4-8 The frequency deviation at the buses for scenario 3 during the DG loss

- **Scenario 4 results**

In the scenario 4, the assumed even is all the 50% DG penetration loss at a specified time. The large share of renewable generation failure from the total electricity production in the network at the 30th second resulted in the curve as shown in the figure 4-9. In this case also, as the bus frequency characteristic curve is the same, the curves for some of the buses are shown below. The obtained curves show that the deviations are reached up to -5% lower limit and 15% upper limit levels.

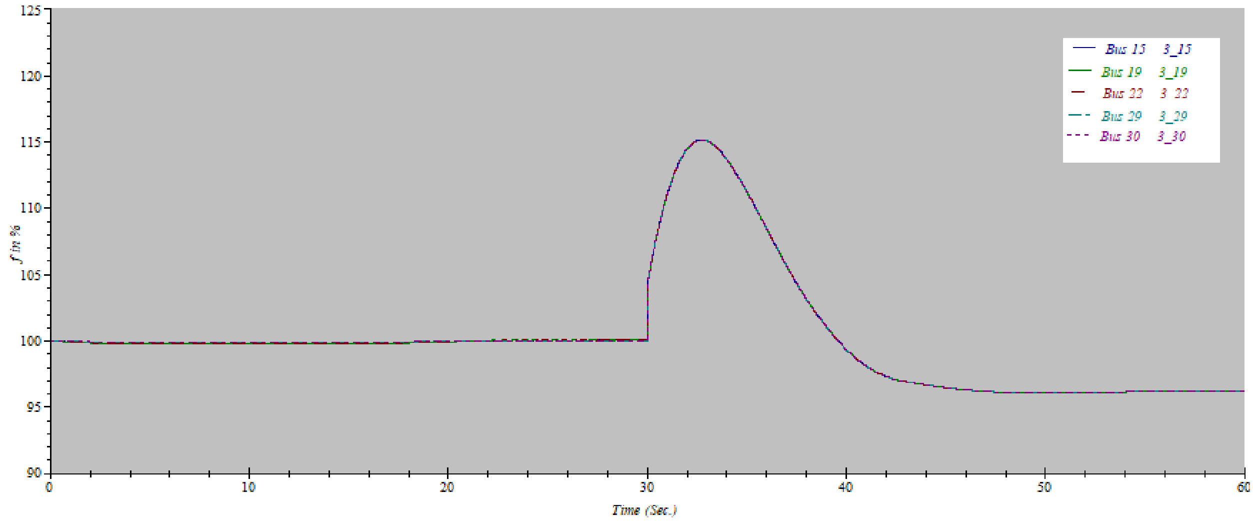

Figure 4-9 The frequency deviation at the buses for scenario 3 during the DG loss

4.4.1. Discussion on transient stability analysis simulated results

From the above graphs from 4-6 to 4-8, that is, the DG integration loss till the 30% of the total electricity production, it proved that the frequency deviations at the 33kV buses are within the 1% limit as set by UK legislative. However, when the DG integration loss reaches beyond or close to 50% (figure 4-9), the frequency deviation at the buses are increasing approximately to -5% to 15 % range from the standard frequency instead of the UK limit of -1% to 1% range. Therefore, from the figures from 4-6 to 4-9, it can conclude that any DG integration below 30% can consider as within the safer limit as per UK legislative frame. Any DG integration above 30% may result in a major stability problem at the grid, and it could generate an adverse influence on the network as well as the pieces of equipment connected with the system. The reason for these changes is due to the decline in the grid inertia because of the introduction of the DG as explained in the section 3.4.3. As more DGs penetrated, the overall inertia in the grid will keep falling. This could lead to a catastrophic failure of the system during the occurrence of the variable output from the renewables. Although the DG without any controls creates problems to the grid, the stored kinetic energy in the wind turbine can be effectively used to support the inertia when it necessary. In the case of PV, the stored energy in the DC capacitor can utilize for the same purpose. Therefore, in the case of DG integration beyond 30% into any electrical power network requires widespread stability analysis.

4.5. Harmonic analysis

Under the harmonic analysis, the harmonic effects due to the power electronics components in the DG network investigated in this thesis. In general, there are many power electronic components present in the DG such as within the wind power and solar network systems. However, here, the harmonics resulted from the solar inverters and its effects on the common coupling points (the buses) only analysed. In this thesis, examined two types of harmonic sources that are normally present within the solar inverter of the model. Then, determined the total harmonic distortion (THD) at each of the distribution buses for all the scenarios. The maximum permitted THD in the UK for 33kV distribution voltage level is 3% at the point of common coupling, and this condition checked for all the scenarios. The two typical harmonic sources (the 6 pulses current source and 12 pulses current source) that assumed in the solar inverters are shown in the figure 3-10 and figure 3-11, and the DGs are connected to the same buses as described in the other analysis.

- **Scenario 1 results**

In the scenario 1, when DG penetration is 15% (10% wind and 5% PV), three solar farms with a total of 15MW capacity is connected to the network. All the solar farm is of 5 MW capacity with each farm consist of five, 1 MW PV arrays. Every PV array uses a solar inverter to convert from DC output to AC. The introduction of harmonics within the inverter at each of the PV arrays resulted in harmonic distortion at the buses. Therefore, the results show that the voltage in the both PV farm connected buses, as well as the neighbouring buses, are distorted. The resulted in THD due to both 6 pulse and 12 pulse type current source inverter at distribution buses in the test feeder network is given in table 4-15. Also, the details about the connected PV farm given in table 4-14.

Parameters	**Values**
Total DG in the network	15%
PV contribution for the DG	33.3%
PV farm connected buses	26,29,30

Table 4-14 The details of PV farms connected in the Scenario 1

Bus Id	**Voltage THD due to 6 pulse current harmonic source**	**Voltage THD due to 12 pulse current harmonic source**
Bus 9	1.57	0.49
Bus 10	1.99	0.79
Bus 12	1.19	0.28
Bus 14	1.23	0.34
Bus 15	1.29	0.42
Bus 16	1.46	0.31
Bus 17	1.81	0.64
Bus 18	1.42	0.18
Bus 19	1.56	0.32
Bus 20	1.66	0.44
Bus 21	1.69	0.23
Bus 22	1.68	0.20
Bus 23	1.96	1.33
Bus 24	3.30	2.64
Bus 25	6.08	4.45

Bus 26	11.94	8.46
Bus 27	6.11	4.24
Bus 29	10.54	7.11
Bus 30	9.46	6.26

Table 4-15 The THD at the distributed buses for the scenario 1

- **Scenario 2 results**

In the scenario 2, the number of PV farms and the inverters used are same as the above scenario. The main difference is that the connected wind farms increased compared with the scenario 1, and hence, the total DG penetration level increased to 25%. Accordingly, the contribution from PV to the overall DG penetration decreased to 20% from the 33.33%. Hence, the results show a slight decrease in THD compared with the previous scenario. The resulted in THD at the each of the distribution buses, and the connected PV details for the scenario 2 given in the table 4-17 and table 4-16, respectively.

Parameters	**Values**
Total DG in the network	25%
PV contribution for the DG	20%
PV farm connected buses	26,29,30

Table 4-16 The details of PV farms connected in the Scenario 2

Bus Id	**Voltage THD due to 6 pulse current harmonic source**	**Voltage THD due to 12 pulse current harmonic source**
Bus 9	1.43	1.07
Bus 10	1.84	1.42
Bus 12	1.11	0.81
Bus 14	1.14	0.85
Bus 15	1.2	0.9
Bus 16	1.26	0.93
Bus 17	1.65	1.26
Bus 18	1.25	0.91
Bus 19	1.35	0.99
Bus 20	1.41	1.05
Bus 21	1.6	1.16
Bus 22	1.59	1.15

Bus 23	1.85	1.59
Bus 24	3.11	2.82
Bus 25	5.75	5.17
Bus 26	11.09	10.55
Bus 27	5.83	4.89
Bus 29	9.99	8.35
Bus 30	8.97	6.73

Table 4-17 The THD at the distributed buses for the scenario 2

- **Scenario 3 results**

In this scenario, three more PV farms and hence, the same number of inverters (5) as in scenario 1 added to the system in additional, and hence, the overall DG penetration grew to 30% and the total number of inverters doubled compared with the previous scenarios. Thus, the PV contribution to the overall DG penetration progressed to 33.33 %, which is the same as in the scenario 1. The results tell that the introduction of new inverters resulted in more distortion at the distribution buses as well as for the other neighbouring buses. The PV details and the THD at the distribution buses given table 4-18 and table 4-19, respectively.

Parameters	**Values**
Total DG in the network	30%
PV contribution for the DG	33.3%
PV farm connected buses	14,17,25,26,29,30

Table 4-18 The details of PV farms connected in the Scenario 3.

Bus Id	**Voltage THD due to 6 pulse current harmonic source**	**Voltage THD due to 12 pulse current harmonic source**
Bus 9	3.12	0.89
Bus 10	3.97	1.37
Bus 12	2.56	0.81
Bus 14	3.52	1.94
Bus 15	2.79	1.09
Bus 16	2.81	0.58
Bus 17	3.55	0.97
Bus 18	2.79	0.43
Bus 19	2.96	0.47

Bus 20	3.08	0.64
Bus 21	3.59	0.63
Bus 22	3.57	0.49
Bus 23	3.59	1.96
Bus 24	5.09	3.36
Bus 25	8.72	6.26
Bus 26	13.54	9.61
Bus 27	7.43	5.17
Bus 29	10.97	7.5
Bus 30	9.75	6.55

Table 4-19 The THD at the distributed buses for the scenario 3

- **Scenario 4 results**

In this scenario, more wind farms added compared with the previous scenario. Therefore, the DG penetration level rose to 50%. However, the number of PV farms maintained the same as in the scenario 3, and hence, the total PV share of the overall DG penetrations diminished to 20% as in the scenario 2. Thus, the voltage distortion at the buses lowered compared with the scenario 3. The PV details and the THD at the distribution buses are given in table 4-20 and table 4-21, respectively.

Parameters	Values
Total DG in the network	50%
PV contribution for the DG	20%
PV farm connected buses	14,17,25,26,29,30

Table 4-20 The details of PV farms connected in the Scenario 4

Bus Id	Voltage THD due to 6 pulse current harmonic source	Voltage THD due to 12 pulse current harmonic source
Bus 9	2.28	0.68
Bus 10	3.07	1.13
Bus 12	1.91	0.58
Bus 14	2.62	1.45
Bus 15	2.1	0.8
Bus 16	2.18	0.49
Bus 17	2.8	0.81

Bus 18	2.13	0.32
Bus 19	2.27	0.4
Bus 20	2.37	0.54
Bus 21	2.73	0.53
Bus 22	2.74	0.43
Bus 23	2.81	1.51
Bus 24	4.11	2.65
Bus 25	7.18	5.05
Bus 26	11.32	7.93
Bus 27	5.91	4.03
Bus 29	9.11	6.16
Bus 30	8.14	5.42

Table 4-21 The THD at the distributed buses for the scenario 4

4.5.1. Discussion on harmonic analysis simulated results

The summary of the resulted total harmonic voltage distortion due to the 6 pulse and 12 pulse current harmonic source solar inverter at the distribution buses are given in the figure 4-10 and figure 4-11, respectively. It can see that the THD distortion due to the 6 pulses current source inverters at all the distribution buses is higher than that of 12 pulses current source inverters for each scenario.

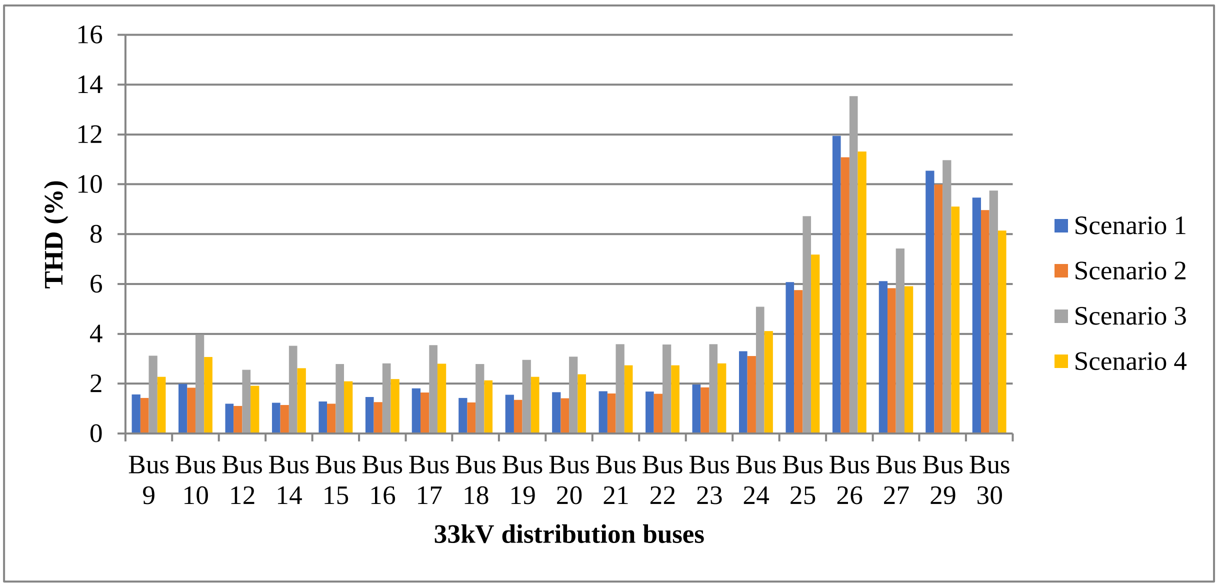

Figure 4-10 Summary of THD due to the 6 pulses harmonic source inverter at the distribution buses.

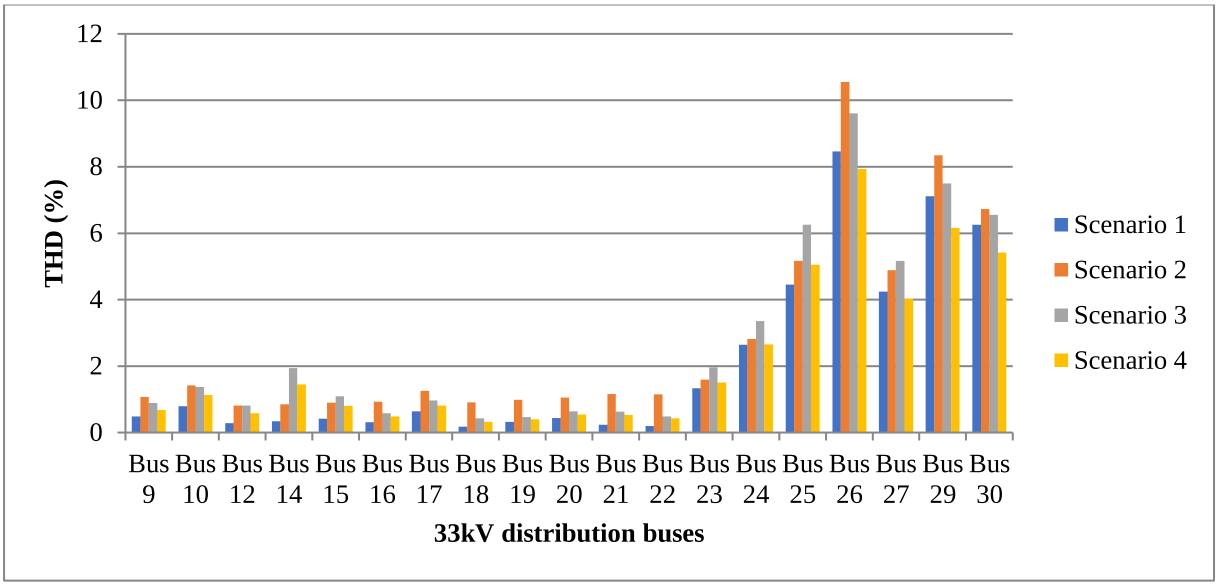

Figure 4-11 Summary of THD due to the 12 pulses harmonic source inverter at the distribution buses.

For all scenarios, there are few distributions buses, at which the THD crossed beyond the UK legislative distortion limit (that is, 3%). Hence, none of the scenarios are valid as per the UK standards. Also, it can notice that the THD at most of the PV farm connected buses increased beyond the acceptable range of 3%. In addition, for all the scenarios, the harmonics generated due to the solar inverter is not only affected the PV farm connected buses but also the neighbouring buses. Furthermore, as the number of solar farms increases, the THD at the buses increased for both 6 pulses and 12 pulses current source inverters. At the same time, as the contribution from the solar PV to the overall DG decreases, the THD is reduced (for instance, scenario 1 & scenario 2 or scenario 3 & scenario 4). Overall, it can conclude that in the case of solar distributed sources, both the 6 pulse and 12 pulses current source inverters require well designed harmonic filters to eliminate harmonics before integrating to the grid. Else, it may lead to several problems as explained in the section 2.5.2. The filter design must be based on the most affected harmonic components (E.g. based on the 3rd harmonic component or the 7th harmonic component etc). In general, the deterioration due to the higher harmonic components can suppress by using a single tuned harmonic filter.

4.6. Summary

In this chapter, the outcomes from the different tests- load flow, short-circuit fault level, transient stability, and harmonic analysis discussed. The simulations of four different scenarios- at 15%,25%,30% and 50% DG penetration levels conducted for each test. The load flow analysis results explicate that any DG integration beyond the 30% is unacceptable as per the UK legislative. Similarly, the transient stability analysis resulted in the frequency variation beyond 1% limit as set by UK legislative for more than 30% DG integration. The short circuit fault level results showed an increased short-circuit fault current level compared with the base network, that is, without a DG for all the scenarios. The scenario 4 results exhibited a large increase from the base network fault current level. Hence, any DG penetration close to 30% requires extensive studies to reconfigure the original network before integrating DG. Therefore, 30% is the maximum penetration level as per the UK standard based on the prototype distribution test feeder. The results obtained from the thesis resembled the recommendation from the IRENA which states that the Smart Grid becomes necessary when the maximum penetration level increased beyond 30% (IRENA, 2013). The harmonic results showed that the THD at the buses crossed the UK legislative THD limit of 3% for all the scenarios. Hence, the use of 6 pulses and 12 pulses current source inverter without a proper harmonic filter would create problems in the network. All the results presented here based on the studies conducted on the IEEE 30 test distribution feeder which assumed as a representative of the original UK electrical network. The subsequent chapter illustrates the conclusion and possible future studies related to this thesis.

5. Conclusion and Future work

5.1. Conclusion

The main goal of this thesis was to study the distributed generation systems and its different impacts while integrating into the grid. As the possibility to use the real existing network was not available, a prototype model, the IEEE 30 bus system was chosen to study the consequences of DG into the distribution network. With the help of previous research papers, general effects are identified and then, studied the severity of the impact based on the DG penetration levels into the grid. Four different scenarios with penetration levels of 15%,25%,30%, and 50% recognized to study the impacts. A few tests had been executed to identify and analyse the impacts. The load flow, the short-circuit fault level, the transient and the harmonic analysis was picked to study the impacts on voltage, fault level current, frequency, and harmonics. The electricity produced by the PV and wind picked as the distributed system in this thesis. Different models were developed in the ETAP software based on the penetration levels as well as the picked tests and executed several simulations to study about some of the identified impacts.

Based on the studies and simulation results it can be concluded that:

- Although there are numerous benefits provided by DG, its integration may have a significant impact if the penetration increased beyond a certain limit depending on the electricity network configuration.
- The introduction of the distributed system changes the tradition radial flow of conventional power network, that is, power flow in one direction, and hence it contributes to various problems.
- The increased penetration of the DG changed the magnitude of voltage at the common coupling point, that is, the voltage at the bus. As every country has an upper and lower limit for the maximum permitted voltage variation, the DG penetration above a certain limit would cause problems to the grid. In this thesis, the upper limit identified as 30 % based on a representative robust UK power network model and the UK legislative frame.
- As most of the distributed generation sources are intermittent, the increased penetration would affect the stability of the network. In this thesis, the frequency at the common coupling point proved within the UK permitted upper limit when penetration is below 30%. However, when the penetration increased near to 50%,

ended with significant deviations from the standard frequency. This study is valid for all countries, as every country have an upper and lower limit on the frequency.

- In general, the presence of the DG into the distributed network increased the fault level currents. A penetration close to 50% resulted in a large variation in the short-circuit current at the common coupling points compared with the base network without DG. Among the different faults, the single line to ground fault appeared much deviation from the base network. As design and configuration of protection and other types of equipment based on the fault level current, the increased penetration level might cause catastrophic failure of the entire power network.
- The presence of the power electronic components without a suitable filter generated harmonic distortion beyond the UK permitted limit at the common coupling points. As per the harmonic results from the thesis, the 6-pulses and 12-pulses current source inverters shall not use within the power electronic components of DG without a harmonic filter.
- In general, it proved that the voltage and fault current at the common coupling points are depending on the location, type, penetration level, and distance of the DG.

Overall, it can conclude that although DG has proven suitable to solve some of the modern world challenges, the higher penetration of DG into the network can create adverse effects on the power system. Hence a thorough technical analysis and suitable precautionary actions are required to avoid the problem that may create due to the DG integrations.

5.2. Future work and Recommendations

Although the thesis covered some of the commonly occurred DG integration issues, several similar and future studies can extend from this dissertation.

- The results of the studies based on a prototype IEEE model. Therefore, a real existing network can be modelled based on the currently used real-time parameters.
- The chosen network in this thesis considered as a robust network, hence, a similar study can be conducted based on a non-robust network by adjusting the suitable parameters of the current model.
- The load flow study explained in this thesis mainly focussed on the magnitude of the voltage. Therefore, a detailed study can conduct after including the other parameters such as voltage phase angle, active and reactive power, etc.

- In this thesis, the fault level current is focussed only on one IEC parameter, the initial symmetrical short-circuit current. However, a detailed study can be executed by including the other IEC parameters such as peak short-circuit current, steady-state short-circuit current, etc. Also, the current study shall extend with a sensitivity analysis of fault at other parts of the selected model.
- The short-circuits fault level analysis also can be extended to know the impacts on the protection system and its effect on the protection coordination when integrating DG into the network.
- The transient stability analysis of this thesis is based only on one type of event, that is, loss of DG penetration. A detailed study can conduct by including the other type of commonly occurring events such as the frequency response of the system during a fault occurrence.
- The similar type of transient stability analysis as described in the thesis can plan by incorporating the dynamic models of DGs and other control systems.
- The harmonic analysis of the thesis limited on the solar inverter. As many power electronic components used in the current DG systems, a detailed study can plan after incorporating all power electronic components. For instance, the harmonic effect due to power electronic converter used in wind turbine. Furthermore, the studies can conduct by including harmonic filters to know the aftereffects.
- All the studies that handled in the thesis based on the mix of different distributed sources that is a combination of PV and wind. However, the individual effect due to wind and PV not extensively covered in this thesis. Hence, as future work, such studies can be conducted for each of the distributed generations. As an extension, other DGs such as from biomass, fuel cell etc. can be included.
- This thesis didn't cover an extensive design of PV and wind model. Hence, a detailed model can be created by considering all parameters, and similar studies as described in this thesis can plan as future work.
- The studies carried here based on the doubly-fed induction generator type DG; hence, similar studies can be executed based on the other wind turbine types.
- The selection of buses for the DG integration based on a high-level analysis; hence, a detailed sensitivity analysis can be conducted as future work to know the effects due to DG integration at each of the buses on selected feeder model.

- Since in most of the cases the data acquisition systems are not available, integrating DG into distribution network is complex; therefore, the information system such as the "supervisory control and data acquisition" (SCADA) system can be used to do a similar study of the power system operation before and after the DG integration.
- As higher penetration levels are uncertain and have a negative impact on the power systems, a future study could be extended to identify the techniques suitable to maintain the stability and safe operation of the electric network for renewable penetration.

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A. Appendix 1

1. Line parameters of the IEEE 30 bus system

Serial No:	From Bus ID	To Bus ID	R_{Pu}	X_{Pu}
1	1	2	0.0192	0.0575
2	1	3	0.0452	0.1652
3	2	4	0.0570	0.1737
4	3	4	0.0132	0.0379
5	2	5	0.0472	0.1983
6	2	6	0.0581	0.1763
7	4	6	0.0119	0.0414
8	5	7	0.0460	0.1160
9	6	7	0.0267	0.0820
10	6	8	0.0120	0.0420
11	6	9	0.0000	0.2080
12	6	10	0.0000	0.5560
13	9	11	0.0000	0.2080
14	9	10	0.0000	0.1100
15	4	12	0.0000	0.2560
16	12	13	0.0000	0.1400
17	12	14	0.1231	0.2559
18	12	15	0.0662	0.1304
19	12	16	0.0945	0.1987
20	14	15	0.2210	0.1997
21	16	17	0.0524	0.1923
22	15	18	0.1073	0.2185
23	18	19	0.0639	0.1292
24	19	20	0.0340	0.0680
25	10	20	0.0936	0.2090
26	10	17	0.0324	0.0845
27	10	21	0.0348	0.0749
28	10	22	0.0727	0.1499
29	21	22	0.0116	0.0236
30	15	23	0.1000	0.2020
31	22	24	0.1150	0.1790
32	23	24	0.1320	0.2700
33	24	25	0.1885	0.3292
34	25	26	0.2544	0.3800
35	25	27	0.1093	0.2087
36	28	27	0.0000	0.3960
37	27	29	0.2198	0.4153
38	27	30	0.3202	0.6027
39	29	30	0.2399	0.4533
40	8	28	0.0636	0.2000
41	6	28	0.0169	0.0599

Table A-1 The line parameters of IEEE 30 bus system

2. Per unit bus voltage magnitude of the IEEE 30 bus system

Bus ID	Bus voltage magnitude (p.u)
1	1.060
2	1.043
3	1.021
4	1.012
5	1.010
6	1.010
7	1.002
8	1.010
9	1.051
10	1.045
11	1.082
12	1.057
13	1.071
14	1.042
15	1.038
16	1.045
17	1.040
18	1.028
19	1.026
20	1.030
21	1.033
22	1.033
23	1.027
24	1.021
25	1.017
26	1.000
27	1.023
28	1.007
29	1.003
30	0.992

Table A-2 Per unit bus voltage magnitude of IEEE 30 bus system.

3. The transformer tapping settings of IEEE 30 bus system

Bus		Tap setting values in p.u.
From	To	
4	12	0.932
6	9	0.978
6	10	0.969
28	27	0.968

Table A-3 The transformer tapping settings of IEEE 30 bus system.

4. The generator ratings of the IEEE 30 bus system

Bus	Generator	
	MW	MVAR
1	260.1	-16.8
2	40	50
5	0	36.845
8	0	37.125
11	0	16.189
13	0	10.646

Table A-4 The generator settings of IEEE 30 bus system.

B. Appendix 2

The load flow report of the IEEE 30 bus network has given below. This report generated by using the software ETAP.

Project:	IEEE 30 BUS	ETAP	Page:	1
		16.0.0C	Date:	08-05-2018
Contract:			SN:	4359168
Engineer:		Study Case: LF	Revision:	Base
Filename:	IEEE30BUS		Config.:	Normal

LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
* Bus 1 13_1	132.000	106.000	0.0	260.965	-16.800	0	0	Bus 2 13_2	173.236	-21.341	720.2	-99.2	
								Bus 3 13_3	87.729	4.541	362.5	99.9	
Bus 2 13_2	132.000	104.314	-5.4	40.000	50.000	21.700	12.700	Bus 1 13_1	-168.050	31.033	716.5	-98.3	
								Bus 4 13_4	43.625	3.947	183.7	99.6	
								Bus 5 13_5	82.385	1.822	345.5	100.0	
								Bus 6 13_6	60.340	0.499	253.0	100.0	
Bus 3 13_3	132.000	102.075	-7.5	0	0	2.400	1.200	Bus 1 13_1	-84.614	2.426	362.7	-100.0	
								Bus 4 13_4	82.214	-3.626	352.6	-99.9	
Bus 4 13_4	132.000	101.178	-9.3	0	0	7.600	1.600	Bus 2 13_2	-42.610	-4.738	185.3	99.4	
								Bus 3 13_3	-81.357	5.220	352.4	-99.8	
								Bus 6 13_6	72.150	-16.314	319.8	-97.5	
								Bus 12 3_12	44.216	14.231	200.8	95.2	-6.800
* Bus 5 13_5	132.000	101.000	-14.2	0.000	36.845	94.200	19.000	Bus 2 13_2	-79.433	6.172	345.0	-99.7	
								Bus 7 13_7	-14.767	11.674	81.5	-78.4	
Bus 6 13_6	132.000	101.026	-11.1	0	0	0	0	Bus 2 13_2	-58.393	1.467	252.9	-100.0	
								Bus 4 13_4	-71.516	17.601	318.9	-97.1	
								Bus 7 13_7	38.119	-2.958	165.5	-99.7	
								Bus 8 13_8	29.568	-8.065	132.7	-96.5	
								Bus 28 13_28	18.668	-0.026	80.8	100.0	
								Bus 9 1_9	27.715	-8.175	125.1	-95.9	-2.200
								Bus 10 3_10	15.838	0.157	68.6	100.0	-3.100
Bus 7 13_7	132.000	100.238	-12.9	0	0	22.800	10.900	Bus 5 13_5	14.938	-13.307	87.3	-74.7	
								Bus 6 13_6	-37.738	2.407	165.0	-99.8	
* Bus 8 13_8	132.000	101.000	-11.8	0.000	37.125	30.000	30.000	Bus 6 13_6	-29.458	7.530	131.7	-96.9	
								Bus 28 13_28	-0.542	-0.405	2.9	80.1	
Bus 9 1_9	33.000	105.088	-14.1	0	0	0	0	Bus 10 3_10	27.713	5.921	471.8	97.8	
								Bus 6 13_6	-27.714	9.803	489.4	-94.3	
								Bus 11 1_11	0.000	-15.724	261.8	0.0	
Bus 10 3_10	33.000	104.508	-15.7	0	0	5.802	-18.752	Bus 9 1_9	-27.713	-5.121	471.8	98.3	
								Bus 17 3_17	5.324	4.424	115.9	76.9	
								Bus 20 3_20	9.021	3.707	163.3	92.5	
								Bus 21 3_21	15.785	10.013	312.9	84.4	
								Bus 22 3_22	7.618	4.601	149.0	85.6	
								Bus 6 13_6	-15.837	1.127	265.8	-99.7	
* Bus 11 1_11	11.000	108.200	-14.1	0.000	16.189	0	0	Bus 9 1_9	0.000	16.189	785.3	0.0	
Bus 12 3_12	33.000	105.708	-14.9	0	0	11.200	7.500	Bus 14 3_14	7.860	2.402	136.0	95.6	

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
								Bus 15 3_15	17.900	6.796	316.9	93.5	
								Bus 16 3_16	7.252	3.354	132.2	90.8	
								Bus 4 13_4	-44.211	-9.544	748.6	97.7	
								Bus 13 1_13	0.000	-10.508	173.9	0.0	
* Bus 13 1_13	11.000	107.100	-14.9	0.000	10.646	0	0	Bus 12 3_12	0.000	10.646	521.7	0.0	
Bus 14 3_14	33.000	104.224	-15.8	0	0	6.200	1.600	Bus 12 3_12	-7.785	-2.247	136.0	96.1	
								Bus 15 3_15	1.585	0.647	28.7	92.6	
Bus 15 3_15	33.000	103.764	-15.9	0	0	8.200	2.500	Bus 12 3_12	-17.683	-6.368	316.9	94.1	
								Bus 14 3_14	-1.579	-0.642	28.7	92.6	
								Bus 18 3_18	6.021	1.598	105.0	96.7	
								Bus 23 3_23	5.041	2.912	98.2	86.6	
Bus 16 3_16	33.000	104.435	-15.5	0	0	3.500	1.800	Bus 12 3_12	-7.198	-3.241	132.2	91.2	
								Bus 17 3_17	3.698	1.441	66.5	93.2	
Bus 17 3_17	33.000	103.986	-15.9	0	0	9.000	5.800	Bus 10 3_10	-5.310	-4.387	115.9	77.1	
								Bus 16 3_16	-3.690	-1.413	66.5	93.4	
Bus 18 3_18	33.000	102.811	-16.5	0	0	3.200	0.900	Bus 15 3_15	-5.983	-1.519	105.0	96.9	
								Bus 19 3_19	2.783	0.619	48.5	97.6	
Bus 19 3_19	33.000	102.561	-16.7	0	0	9.500	3.400	Bus 18 3_18	-2.778	-0.609	48.5	97.7	
								Bus 20 3_20	-6.722	-2.791	124.2	92.4	
Bus 20 3_20	33.000	102.970	-16.5	0	0	2.200	0.700	Bus 10 3_10	-8.939	-3.525	163.3	93.0	
								Bus 19 3_19	6.739	2.825	124.2	92.2	
Bus 21 3_21	33.000	103.268	-16.1	0	0	17.500	11.200	Bus 10 3_10	-15.674	-9.773	312.9	84.9	
								Bus 22 3_22	-1.826	-1.427	39.3	78.8	
Bus 22 3_22	33.000	103.321	-16.1	0	0	0	0	Bus 10 3_10	-7.565	-4.493	149.0	86.0	
								Bus 21 3_21	1.827	1.428	39.3	78.8	
								Bus 24 3_24	5.739	3.065	110.2	88.2	
Bus 23 3_23	33.000	102.714	-16.3	0	0	3.200	1.600	Bus 15 3_15	-5.009	-2.849	98.2	86.9	
								Bus 24 3_24	1.809	1.249	37.4	82.3	
Bus 24 3_24	33.000	102.154	-16.5	0	0	8.700	2.213	Bus 22 3_22	-5.693	-2.994	110.2	88.5	
								Bus 23 3_23	-1.803	-1.237	37.4	82.5	
								Bus 25 3_25	-1.204	2.018	40.2	-51.3	
Bus 25 3_25	33.000	101.729	-16.1	0	0	0	0	Bus 24 3_24	1.214	-2.000	40.2	-51.9	
								Bus 26 3_26	3.545	2.367	73.3	83.2	
								Bus 27 3_27	-4.759	-0.366	82.1	99.7	
Bus 26 3_26	33.000	99.961	-16.5	0	0	3.500	2.300	Bus 25 3_25	-3.500	-2.300	73.3	83.6	
Bus 27 3_27	33.000	102.319	-15.5	0	0	0	0	Bus 25 3_25	4.783	0.412	82.1	99.6	
								Bus 29 3_29	6.190	1.669	109.6	96.6	
								Bus 30 3_30	7.092	1.663	124.6	97.4	
								Bus 28 13_28	-18.065	-3.744	315.5	97.9	

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
Bus 28 13_28	132.000	100.682	-11.7	0	0	0	0	Bus 6 13_6	-18.610	-1.091	81.0	99.8	
								Bus 8 13_8	0.544	-3.940	17.3	-13.7	
								Bus 27 3_27	18.066	5.032	81.5	96.3	-3.200
Bus 29 3_29	33.000	100.335	-16.8	0	0	2.400	0.900	Bus 27 3_27	-6.104	-1.506	109.6	97.1	
								Bus 30 3_30	3.704	0.606	65.4	98.7	
Bus 30 3_30	33.000	99.188	-17.7	0	0	10.600	1.900	Bus 27 3_27	-6.930	-1.358	124.6	98.1	
								Bus 29 3_29	-3.670	-0.542	65.4	98.9	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

# Indicates a bus with a load mismatch of more than 0.1 MVA