Study on Impacts and Penetration Factor of Solar Energy Integration on National Grid System of Bangladesh Using DIgSILENT/ PowerFactory

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Supervisor's Declaration

The MS level research on "Study on Impacts and Penetration Factor of Solar Energy Integration on National Grid System of Bangladesh Using DIgSILENT/ PowerFactory" has been carried out and the dissertation was prepared under my direct supervision. Hereby I confirm that, to the best of my knowledge the thesis represents the original research work of the candidate; the contribution made to the research by me, by others of the University was consistent with normal supervisory practice, and external contributions to the research are acknowledged.

I believe the thesis to be in a suitable presentational form and ready for examination.

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Candidate's Declaration

I confirm that this thesis represents my own work; the contribution of any supervisors and others to the research and to the thesis was consistent with normal supervisory practice. External contributions to the research are acknowledged.

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ABSTRACT

Interconnection of a distributed generator (DG) like Solar PV generator to an existing distribution system provides various benefits like improved power quality, higher reliability of the distribution system and covers peak shaves. This type of generators has negative impacts on voltage and frequency stability, transmission and distribution losses, and transient stability of an existing central grid system. In this research the impacts of DG/PV penetration on the national grid of Bangladesh grid have been studied and the maximum penetration factors for different feeders have been investigated. The studies have compared the impacts on grid with PV integration and without PV integration through simulating the standard bus test feeder using DigSILENT software. Two case studies at loaded Dhanmondi feeder of Dhaka and Housing feeder of Comilla S & D- 2 reveal that, integration of solar PV generation causes the grid system to lose its radial power flow frequently when grid voltage exceeds the maximum tolerable limit of bus voltage 0.95 to 1.05 per unit (p.u.) as of the national grid standard of Bangladesh. There was a decrease in total power losses as losses of transmission and distribution buses and lines increases, besides the increased fault level of the system caused by the DG. The study also shows that, for a feeder of rural area in Bangladesh like Housing feeder of Comilla S & D- 2, the maximum penetration should be not more than 23.43% of the total generation.

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Table Of Contents

List Of Tables:

List Of Figures:

CHAPTER 1

1. BACKGROUND

1.1 Introduction

Fossil energy is the major share of world energy consumption. Oil, natural gas and coal together constitute 80% of global energy consumption. But the development of fossil energy is significantly dominated by the concern of global air pollution, water pollution, coastal pollution, deforestation and global climate deterioration. In response to control the global consequences, Photovoltaic (PV) technology has in recent years become a significant form of power generation on electricity networks. Governments of different countries around the world are considerably interested on renewable energy due to reducing energy related environmental problems, specially CO_2 emission and energy security. A new large and inexhaustible source of energy that has capability to generate power requirements of the world on a contained basis is simply called "renewable energy". Electricity utilities who manage these networks have raised concerns regarding the impact of high penetration by photovoltaic into these distribution grids. These concerns generally focus on issues of grid management, and operation and planning, particularly where there is variability in PV system output due to cloud cover. Variability in PV irradiance is often cited as a major impediment to high levels of PV penetration into existing electrical networks. The objective of this work is to present the obligations concerning integration of dispersed generation units in the electricity grid as well as to investigate the impact of Photovoltaic plant integration in electricity grid parameters. In order to achieve this purpose a theoretical background is needed and a software which is using it in order to compute the results. In order to investigate the obligations of dispersed generation units in terms of static and dynamic grid support, Bangladesh grid code is taken into consideration.

Bangladesh is a developing country. At present, 64% of the total population has access to electricity (including renewable energy). The present share of renewable energy except hydro in Bangladesh is only 1%. Bangladesh aims to develop the indigenous energy resources which play a vital role in the socioeconomic development of the country. In this work, main purpose is to show the impact of PV generation in Bangladesh power with system's static and transient voltage stability for different aspects.

1.2 Literature Study

Energy is the main issue of rapidly advancing world. Growing concerns of energy security, significantly falling reserve margin of fossil fuels and skyrocketing prices of fossil fuels, war among different countries due to possession of fossil fuels and greenhouse gas emission control have heightened interest in the harnessing of renewable energy resources. As a result, exploitation and utilization of sustainable energy have become key factors adopted in energy consumption adjustment in every country. Among various sustainable power generation methods, grid-connected photovoltaic (PV) generation has been exploited and utilized around the world. It is reported that the grid-integrated PV around the world has been up to 92% of the total PV installation at the end of 2007 [1]. However, the integration of high fraction of renewable energy such as Solar Photovoltaic into the electrical transmission grid brings with it a host of technical challenges. The lack of understanding and technical know-how to resolve these challenges has preempted the development of renewable energy in many countries, especially in Bangladesh. The inherently intermittent nature of renewable energy sources poses operational, efficiency and reliability challenges to current power systems due to temporal fluctuations, geographical dispersion of renewable energy sources and inadequacy of the existing power grid [2]. The inherently intermittent nature of renewable energy sources poses operational, efficiency and reliability challenges to current power systems due to temporal fluctuations, geographical dispersion of renewable energy sources and inadequacy of the existing power grid. The operating characteristic of renewable resources which are strongly influenced by weather patterns has a profound impact on the planning and operation of the power grid. There are two characteristics of power supply from renewable energy resources which present significant obstacles to their large-scale integration into the power grid. Renewable energy production is uncertain and cannot be forecasted accurately. Furthermore, it exhibits a highly variable diurnal pattern, so that even if perfect forecasts were possible, integrating massive amounts of renewable energy resources into the power grid presents significant challenges in terms of the dispatch, reserves, and ramping requirements [3]. The successful connection of equipment to the electrical grid requires that basic power quality requirements be met for harmonics, voltage, and frequency. Renewable energy generators, with their associated power electronics, generate harmonics and have electrical characteristics under voltage and frequency excursions that may make it difficult to meet those requirements. Furthermore, the variability of renewable resources, due to characteristic weather fluctuations, introduces uncertainty in generation output on the scale of seconds, hours and days. Concerns about power system reliability thus limit the amount of renewable energy that power utilities and transmission system operators allow to be connected to the grid. Large-scale PV systems integration presents a spectrum of technical challenges arising mostly from the expanding application of power electronic devices at high power ratings. The connection of renewables at the distribution levels also requires significant modification of the distribution design to accommodate bidirectional power flow. The amount of Solar PV penetration has a significant impact on the transmission systems and some cases require a huge investment in transmission expansion because of capacity. Facilitating the integration of distributed energy resources requires innovations in micro-grid and energy management systems that transparently provide control and regulation.

However, DG/PV integration into distribution networks leads to a number of challenges. For instance, with significant penetration of DG power flow reversal may be experienced and the distribution network will no longer be a passive circuit. Much research has been conducted on the integration of solar PV into the transmission grid and distribution system. Modeling of a large grid-integrated PV station and analysis of its impact on grid voltage is reported in [4]. The paper used DIgSILENT/ Power Factory to model and simulate grid integrated solar PV. In the simulation, a 100 MW grid-connected solar PV station is connected to the grid via 500 kV line through a node, while a PV station is paralleled at another node where the voltage level is 110 kV. The power generated from the PV array is fluxed to a 10 kV bus and the voltage is boosted to 110 kV transformers whose capacity is 120MVA. From the simulation results, it was discovered that the output of the PV station changes with the variation of temperature and irradiance in one day. Additionally, there is always a power drop for the loss about 5% in the inverter. With reference to nominal voltage, the total voltage variation range is about 0.024 p.u.

The impact of a grid-connected PV system on the steady-state operation of a Malaysian grid is presented in [5]. The main object of the research was to investigate the voltage profile and power losses of a grid connected solar PV system for residential, commercial and industrial load pattern categories at Peninsular Malaysia. After data collection, the study modeled the photovoltaic generator as a negative load connected to the distribution generation bus. The single line diagram voltages were 132 kV/11 kV. For commercial load category (> 1MW) it was discovered that the voltage increases from 6:00am to 6:00pm, but the voltage rise did not cause over-voltage when compared with the standard permissible voltage of 1.05 p.u. in Malaysia. The study also concluded that there was some substantial reduction in power losses when the solar PV was injected into the grid.

In Europe, the High Penetration of very large scale PV Systems into the European Electric Network was reported in [11]. In EU 2020 projected power generation mix of 87 GW of PV installed capacity (25 GW installation in North Africa imported in the EU grid and 50 GW of installed capacity distributed among the EU countries). Using Matpower v4.0 (a suite of MATLAB) simulation was done to investigate the effect of increased PV power generation in the European high voltage transmission network. Cross-border parallel-interconnected nodes were assumed to be 380 kV. The study reported that distributed grid operators are faced with technical challenges such as voltage rises, reactive power control, and islanding from high penetration LV/MV levels. Again, both scenarios (first 25 GW installations in North Africa and second 50 GW among the EU Countries) require a revision and an upgrade of the transmission grid in order to avoid congestion. The study concluded that the second scenario ends up being less critical than the first one.

Characterization of the solar power impact in the grid was analyzed in [6] to predict the response at various penetration levels on the grid. For a more realistic approach, existing installation (1.06 MWp) was used for the studies to create new modules for solar power series. The study used Markov Matrices to simulate series. Three penetration scenarios were carried out in this study, namely 5MWp, 10MWp and 15MWp for different seasons and during day and night. The studies concluded that additional injection of solar PV into the grid affects voltage at all the buses. For 15 MWp penetration in the month of August, which could be the most critical case, the network was able to accommodate the penetration, hence the conclusion that the Belgian grid is able to accommodate solar PV power until 15 MW pat least. Studies for higher penetration levels were recommended.
The paper also shows the effect of concentrated PV penetration on the degree of system stability [7]. It was reported that for all the buses, increased PV penetration has a negative impact on system stability. The manner of PV integration (whether concentrated or dispersed), location and size all have a direct impact on system static voltage stability. It was also discovered during the study that voltage stability deteriorates with the integration of power factor operated PV, whereas in some instances voltage stability improves with the integration of voltage control mode operated PV.

Several study or research has been conducted to show the impact of large scale solar PV integration on the transmission and distribution system of Bangladesh. But very few considered the original grid data and solar radiation data of relevant sites. So the impact analysis does not show the actual grid condition and the impacts that actually can be happened on Bangladesh grid system in near future when large-scale solar generation will come into operation.

The paper represents the impact of large-scale photovoltaic generation on Bangladesh power system stability [8]. First, the model of PV based generator has been analyzed. Then system-loading margin is studied without and with PV based generator. The contribution of PV based generator on solving under voltage problem and improving bus voltage is studied in the paper. This paper will also show the solution of overloading problem of power transformers with solar PV generator. The transient voltage, angle and frequency stability with PV based generator is discussed also. But this paper did not show that, what percentage or level of penetration will create instability.

The paper [9] investigates the impacts of integrating a large photovoltaic solar plant in a practical 11kV urban distribution system. The test system has been simulated using Power System Analysis Toolbox (PSAT). Impact on voltage stability and losses were studied at various generation sizes of the solar plant. Results showed that increased penetration of solar plant improves loading capacity of the test system while leading to increased losses as well as overvoltage phenomenon. This paper also doesn't show the degree of variability.

This High penetration of solar PV is bound to have a significant impact on the transmission grid; a lack of widespread understanding of the technical implications of solar PV integration is stunting the development of renewable energy projects in many countries, including Bangladesh as Bangladesh has taken a good number of renewable energy projects. Moreover, there hasn't been any similar research work on the technical challenges and impact of the integration of high penetration of Photovoltaic (PV) systems into Bangladesh transmission or distribution grid.

1.3 The Objective of this study

The Objectives of this study are

- To analyze the impacts of Solar PV Integration on Grid
- Load or Power Flow analysis during steady state of a Power System.
- To compare the grid voltage stability of a feeder of Bangladesh without PV and with PV
- To find out the critical point of bus instability
- To find out the maximum Percentage of Penetration of PV solar to a Feeder in Bangladesh.

1.4 Thesis Organization

This thesis is organized as follows:

Literature reviews on renewable energy integration in national electrical grid, aim and objectives of the thesis has been presented here.

In chapter 2 distributed generation concept and discussion on technologies are given here. This chapter commences with distributed generation concept which embodies definition, classifications and environmental friendliness of distributed generation. The structure, operation and characteristics of the solar cell are also discussed. This is followed by a brief review of sun and wind based generation as typical technology with their history, classifications and operating principles.

In chapter 3 distributed generation integration Issues presented the recent scenarios of solar energy integration in grid. At first the chapter aims to begin with a deeper consideration of the DG renaissance. Thereafter highlights the threat or challenges posed by DG integration.

In chapter 4 the national electrical grid code of Bangladesh are given which focuses on the flexibility and allowable limits of power quality factors of national grid of Bangladesh.

In chapter 5 a brief has been given on the analysis tool like the popular DigSILENT Simulation Software. This software has been used over the research work.

The chapter 6: Modeling and Simulation depicts detailed description of the grid model and its elements as well as simulation results to show the impacts of DG on distribution network.

The chapter 7: Conclusion and Recommendations presents conclusions of the thesis. The findings of the thesis and some recommendations about DG integration are illustrated in this chapter.

CHAPTER 2

2. DISTRIBUTED GENERATION CONCEPT AND TECHNOLOGY

2.1 Introduction

This chapter commences with distributed generation concept which embodies definition, classifications and environmental friendliness of distributed generation. This is followed by a brief review of sun and wind based generation as typical technology examples. The approach to these reviews includes history, classifications and operating principles.

2.2 Distributed Generation Concept

Distributed generation is not a new concept because originally, all energy was produced and consumed at or near the process that required it [10]. According to them a fireplace, wood stove, and candle are all forms of "distributed" – small scale, demand-sited – energy. So is a pocket watch, alarm clock, or car battery. However, the key to today's energy revolution involves turning the resource clock backwards (from large power plants hundreds or thousands of miles away to a "heat engine" in the building) by riding the rapidly accelerating technology wave forward. Therefore, distributed generation is a fairly new concept in the economics literature about electricity markets, but the idea behind it is not new at all [11].

2.2.1 Definition of Distributed Generation

The reasons for the birth of distributed generation have been highlighted in Chapter 1. Many terms have emerged to describe power that comes from sources other than from large, centrally dispatched generating units connected to a high-voltage transmission system or network [12]. In fact, according to them, there is no clear consensus as to what constitutes distributed generation. However, there appears to be an apparent consensus that basically the connection of generation sources to the distribution network has come to be known as distributed power generation system (DPGS) – most simply as distributed generation (DG) – or the use of distributed energy resources (DER). The term distributed energy resources includes both distributed generation and controllable load [13]. This means that DG is a subset of DER. The term distributed generation can be considered to be synonymous and interchangeable with the terms embedded generation and dispersed generation, which are now falling into disuse [13], [14]. The term 'embedded generation' comes from the concept of generation embedded in the distribution network while 'dispersed generation' is used to distinguish it from central generation [15], [13]. Ackermann *et al*. had suggested the term *embedded distributed generation* if the power output of distributed generation is used only within the local distribution network [16]. Furthermore, a regional coloration to these synonyms has been noted by the author [16] as follows:

Anglo-American countries often use the term 'embedded generation', North American countries the term 'dispersed generation', and in Europe and parts of Asia, the term 'decentralized generation' is applied for the same type of generation.

But the production of electricity by some consumers using their own generation sources with the goal of feeding their loads or as backup sources to feed critical loads in case of emergency and utility outage is defined as "distributed generation" (DG) in North American terms and "embedded generation" in European terms [17]. Distributed generation is a common term in South Africa although Eskom uses embedded generation in its documentations such as DISTRIBUTION STANDARD FOR THE INTERCONNECTION OF EMBEDDED GENERATION in which an Embedded Generator refers to the item of generating plant that is or will be connected to the Distribution network. This definition includes all types of connected generation, including co-generators and renewables.

Keyhani *et al*. assert that distributed generation entails using many small generators of 2 to 50 MW output, situated at numerous strategic points throughout cities and towns, so that each provides power to a small number of consumers nearby and dispersed generation refers to use of even smaller generating units, of less than 500 kW output and often sized to serve individual homes or businesses [18]. In their view later publications tend to combine the two categories into one (i.e., distributed generation), to refer to power generation at customer sites to serve part or all of customer load or as backup power, or, at substations, to reduce peak load demand and defer substation capacity reinforcements.

Also "Engineering guide for integration of distributed generation and storage into power distribution systems" has studied that there are other terms that are commonly used and have certain legal ramifications per utility normal practice, state and federal regulations [19]. Terms such as non-utility generator (NUG), independent power producer (IPP), and qualifying facility (QF) are examples. Others are self-generation, on-site generation, cogeneration, and "inside the fence generation" [20] and small-scale generation [21].

Irrespective of the aforementioned interchangeability, some authors believe distributed generation and dispersed generation are not the same though same acronym – (DG). Their disagreement hinges on capacity as shown in Table 2.1.

Table 2.1: Difference between distributed generation and dispersed generation based on capacity [22]

Distributed Generation	Dispersed Generation	Authors
15 – 10,000kW	10 – 250kW	Willis and Scott (2000)
2 – 5MW	<500kW	Kothari and Nagrath (2003)
10 – 10,000kW	1 – 100kW	Farret and Simões (2006)

Therefore, the different terms often refer to different aspects or properties of the new types of generation [21].

2.2.2 Distributed Generation Classifications

One of the classifications of DGs is based on capacity or output power rating as shown in Table 2.2. The units installed on distribution systems will typically be no larger than 1 or 2 MW [23].

Table 2.2: Distributed generation capacities [16], [24]

Class	Power Range
Micro distributed generation	~ 1W – 5kW
Small distributed generation	5kW – 5MW
Medium distributed generation	5MW – 50MW
Large distributed generation	50MW – 300MW

Another basis for classification of DGs is the type of technology involved in the power generation. Therefore, distributed generation technologies can be categorized as renewable and non-renewable as depicted in Table 2.3.

Table 2.3: Distributed generation technologies [14]

Renewables	Non-renewables
Solar	Internal combustion engine (ICE)
Wind	Combined cycle
Geothermal	Combustion turbine
Ocean	Microturbine
	Fuel cell

Non-renewable energy is obtained from sources at a rate that exceeds the rate at which the sources are replenished [25]. For example, if the biogenic origin of fossil fuels is correct, fossil fuels could be consider renewable over a period of millions of years, but the existing store of fossil fuels are being consumed over a period of centuries. Because fossil fuels are being consumed at a rate that exceeds the rate of replenishment, fossil fuels are considered non-renewable. Also renewable energy is energy obtained from sources at a rate that is less than or equal to the rate at which the source is replenished. In the case of solar energy, [25] asserts that because the remaining lifetime of the sun is measured in millions of years, many people consider solar energy as an inexhaustible supply of energy. In fact, solar energy from the sun is finite, but should be available for use by many generations of people. Therefore, solar energy is considered renewable and other energy sources that are associated with solar energy, such as wind and biomass, are also considered renewable.

Distributed generation technologies could also be grouped according to their dispatchability namely dispatchable and non-dispatchable. This is because, according to [26], one of the primary elements in a distributed generation management system is the dispatch strategy: the aspect of control strategy that pertains to the sources and destinations of energy flows. The key difference between the two categories is the controllability of electric power [27]. The dispatchable resources, in general, have the energy stored, and could therefore be called upon at any given time to produce power. This implies that dispatchable units such as conventional generator sets, fuel cells, and microturbines, can be controlled by a central intelligence and relied on to generate according to the needs of the power system [26]. The non-dispatchable resources, on the other hand, inherently do not have any control of the input energy for later use when needed. This means that non-dispatchable technologies generate not as a function of power system needs, but rather as a function of intermittent availability of their energy source.

From the foregoing it can adduced that while non-renewable DG technologies are dispatchable the renewable DG technologies consist of dispatchable and non-dispatchable resources. Hydroelectric, biomass and geothermal are dispatchable resources, whereas, wind, solar and tidal waves would be classified as non-dispatchable resources – most or common renewable energy systems are non-dispatchable.

Variable renewable power plants, in this case non-dispatchable DGs, rely on resources that fluctuate on the timescale of seconds to days, and do not include some form of integrated storage [28]. Output from such plants fluctuates upwards and downwards according to the resource: the wind, cloud cover, rain, waves, tide, etc. Such technologies are often referred to as intermittent, but this term is misleading because the output, aggregated at the system-wide level, does not drop from full power to zero or vice versa, but rather increases and decreases on a gradient as weather systems shift. It is measured in terms of *ramp rate* – the increase / decrease in output as well as the period over which this occurs. Ramp rates may on occasion be steep: wind plants for example are designed to cut out in storm conditions when a certain wind speed is reached, but meteorological forecasting can provide notice of such events. Therefore, the challenge with variable renewable energy is not so much its *variability,* but rather its *predictability*. In other words, if output could be forecast with 100 % certainty the only challenge would be to meet the ramp rates.

The study "Interconnection requirements for distributed generation" defines distributed generation as any type of electrical generator, static inverter or generating facility [29] interconnected with the distribution system that has the potential either

- for feeding a consumer load, where this load can also be fed by, or connected to, the utility electrical distribution system, or
- for electrically paralleling with, or for feeding power back into the utility's electrical distribution system.

This results in yet another classification of DG as either a separate system or parallel system. A separate or standalone system is one in which there is no possibility of electrically connecting or operating the consumer's generation in parallel with the utility's system. The consumer's equipment must transfer load between the two power systems in an open transition or non-parallel mode. If the consumer claims a Separate System, the utility may require verification that the transfer scheme meets the non-parallel requirements. But in a Parallel or Interconnected System (grid-connected), a generator is connected to a bus common with the utility's system, and a transfer of power between the two systems is a direct result. A consequence of such interconnected operation is that the consumer's generator becomes an integral part of the utility system that must be considered in the electrical protection and operation of the utility system. Parallel generators encompass any type of distributed generator or generating facility that can electrically parallel with, or potentially back feed into the utility system.

2.2.3 Distributed Generation and Environmental Friendliness

Keen public awareness of the environmental impacts of electric power generation and efforts to mitigate climate change are crucial to DG renaissance. For instance, fossil fuelled power plants produce sulphur oxides, particulate matter, and nitrogen oxides [30]. Of the former, sulphur dioxide accounts for about 95% and is a by-product of the combustion of coal or oil. The sulphur content of coal varies from 0.3 to 5%. According to these authors, it should be noted that although sulphur does not accumulate in the air it does so in the soil.

Unfortunately some distributed generation technologies could, if fully deployed, significantly contribute to present environmental problems. Therefore, the technologies that can be used for distributed generation cannot be described in general as environmentally friendly. But regarding the main current environmental issue, the increased greenhouse effect, all DG technologies lead to significantly lower emissions than coal-based technologies [16]. According to [31] the contribution of the capital goods to the emissions from fossil fuel power plants is negligible (<5%). On the contrary, in the case of the so-called "zero emission" generation systems, though direct emission due to combustion is zero, indirect emissions linked to construction, maintenance and dismantling have to be considered. This is the case with nuclear power plants, windmills, photovoltaic generators, hydroelectric power plants and power plants using biomass.

Ackermann consider indirect emissions as emissions that occur during the manufacturing of the power unit and the exploration and transport of the energy resources and maintain that the emissions from typical DG technologies are significantly lower than those from coal power stations [16]. They have also noted that combined cycle gas turbines (CCGT) and large hydro units, too, have significantly lower SO_2 and CO_2 emissions than coal power stations. In their view biomass is seen as being CO_2 neutral, as the amount of CO_2 emitted into the atmosphere when biomass is burnt is equal to the amount of CO_2 absorbed during its growth. According to them NOx (nitrogen oxides) emissions of combustion of bio-fuels were reported to be 20 - 40% lower than that of fossil fuel plants, and SO_2 emissions were reported to be insignificant. Also battery storage as well as fuel cells has no direct emissions besides the emissions occurring during the manufacturing process. However, the fuel mix used for the production of the electricity stored in the batteries must be considered in the calculations of the indirect emissions of battery storage. Furthermore, in the case of fuel cells, the indirect emissions also depend on the energy mix that is required to produce hydrogen, as hydrogen cannot be easily exploited in the same way as conventional fossil fuels.

GIZ agree that renewable energies, such as wind energy, allow electricity production without consuming fossil resources and without any direct carbon dioxide emissions [32]. Therefore, just by producing electrical energy, the use of these sources is justifiable and represents in many locations an economical alternative to the use of fossil resources such as coal or oil. A study of 3 installations in the US Midwest that found the CO_2 emissions of wind power ranged from 14 to 33 tonnes (15 to 36 short tons) per GWh of energy produced [22]. Most of the CO_2 emission came from producing the concrete for wind-turbine foundations. To add credence to a holistic or life cycle assessment of environmental friendliness of not just DGs but any other product, UNIDO (2006) has approached this from standardization perspective. Accordingly it submits that environmental protection is an important aim of standardization: the focus here is on preserving nature from damage that may be caused during the manufacture of a product or during its use or disposal after use. For example, the domestic use of a washing machine should generate only a minimum of pollutants

Two different methods of analysis have been applied to study the life cycle of ‘emission-free’ power generation facilities [31] :

- analysis of the process chain which calculates the total energy utilisation and the corresponding emissions for all the materials used (steel, concrete, plastic, etc.);
- input/output analysis which divides a product according to its economic elements while the life cycle is defined as a set of economic activities.

According to [31] a study conducted by [33] has led to retaining the orders of magnitude of Table 2.4 linked to capital goods. Unfortunately, the authors failed to explain why wind power (coast) has less indirect CO_2 emissions than wind power (interior).

Table 2.4: **Indirect greenhouse gas emissions from "zero emission" power plants (construction, maintenance, demolition of plants, complete life cycle)** [31]

Type of construction	Duration of life (years)	Indirect emissions of CO_2 (gCO_2/kWhe)	Use of primary energy (kJprim/kWhe)	kJprim/kJe (%)
Nuclear	40	3	40	1.11
Wind power (coast)	20	9	120	3.33
Wind power (interior)	20	25	350	10.00
Photovoltaic 1996	20	130	3,000	83.33
Photovoltaic 2005	25	60	1,500	41.66
Pumped storage plant	40	8	110	3.06
Micro-hydraulic power plant	40	15	200	5.56
Wood gasification	15	15	260	7.14
Co-combustion of sludge	30	3	40	1.11

Table 2.4 shows that PV cells' indirect CO_2 emissions are higher than those of wind power. This is in agreement with the comparison executed by Jin (2010) of the environmental friendliness between wind turbines and PV cells with a conclusion that wind turbine manufacturing is cleaner than the volume production of solar PV cells. Therefore, wind power makes good sense environmentally and economically. This is because turbine components are generally either recyclable or inert to the environment.

2.3 Distributed Generation Technology

This section considers the technologies deployed in the generation of electrical power from the sun and wind as typical examples of distributed generation technology. The choice of these two sources without any prejudice to other sources such as microturbines, fuel cells, geothermal and internal combustion engines is because of their relevance to the Western Cape Province.

2.3.1 Solar Energy System

Typically, an informed discussion about solar energy is limited by various and confusing notions of what the term *solar energy* actually describes [34]. In his view broadly speaking, *solar energy* could be used to describe any phenomenon that is created by solar sources and harnessed in the form of energy, directly or indirectly – from photosynthesis to photovoltaic.

The sun is a perennial, silent, free, and non-polluting source of energy and is responsible for all life forms on the planet [35]. This means that sun is of great importance for the planet earth and the ecosystem of our society. Succinctly put, when the sun disappears from the universe, we will cease to exist [18]. Therefore, solar energy is the most abundant energy resource on earth but only a minuscule fraction of the available solar energy is used. The solar energy that hits the earth's surface in one hour is about the same as the amount consumed by all human activities in a year [36], [37]. The total solar energy absorbed by the earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year [38], [39]. According to [38] the amount of solar energy reaching the surface of the planet is so vast that in 1 year it is about twice as much as will ever be obtained from all of the Earth's nonrenewable resources of coal, oil, natural gas, and mined uranium combined. Consequently, solar energy appears to be easy alternative next to conventional sources, like electricity, coal and fossil fuels. For instance it is estimated that by 2050, PV (photovoltaic) will provide around 11% of global electricity production and avoid 2.3 gigatonnes (Gt) of CO2 emissions per year [36]. Also by 2050, with appropriate support, CSP (concentrating solar power) could provide 11.3% of global electricity, with 9.6% from solar power and 1.7% from backup fuels (fossil fuels or biomass) [40]. Solar energy reaches the earth in the form of electromagnetic waves (radiation). Rays emitted by the sun, gamma rays, reach the terrestrial orbit a few minutes after they leave the sun surface, crossing approximately 150 million kilometres [35]. Clouds reflect about 17% of sunlight back into space, 9% is scattered backward by air molecules, and 7% is actually reflected directly off the surface back into space. Therefore, eventually the radiation at earth's surface decreases to about 35% less than the level in the stratosphere. At noon on a clear day, the luminous power at the ground level is approximately 1000 W/m^2. Therefore, many factors affect the amount of radiation received at a given location on earth. These factors are [18]:

- season
- humidity

- temperature
- air mass, and
- the hour of the day

Also according to insolation refers to exposure to the rays of the sun, i.e., the word insolation has been used to denote the solar radiation energy received at a given location at a given time [18]. The phrase incident solar radiation is also used; it expresses the average irradiance in watts per square meter (W/m^2) or kilowatt per square meter (kW/m^2).

2.3.1.1 Photovoltaic System

Photovoltaics (PV) ("photo" meaning "light" and "voltaic" referring to electricity) is the direct conversion of sunlight into an electrical potential (a photovoltage) that can be used to provide electric power. A material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current is said to be *photovoltaic* (Masters, 2004). Therefore, the photo-voltaic effect is the process by which an electric potential difference (voltage) is created in a material exposed to light (electromagnetic radiation), which then leads to the flow of electric current [41]. This process is directly related to the photo-electric effect, but distinct from it in that in the case of the photo-electric effect electrons are ejected from the material surface upon being exposed to high enough frequency (energy) light, whereas in the photo-voltaic effect the generated electrons are transferred across a material junction (e.g., PN junction in a photo-diode) resulting in the buildup of a voltage between two electrodes and the flow of direct current electricity. In other words, the energy supply for a solar cell is photons coming from the sun. A photon with short enough wavelength and high enough energy can cause an electron in a photovoltaic material to break free of the atom that holds it. If a nearby electric field is provided, those electrons can be swept toward a metallic contact where they can emerge as an electric current. The PV photon cell charge offers a voltage of 1.1 up to 1.75 electron volt2 (eV2) with a high optical absorption [18].

It is concur with other myriad authors that the PV effect itself was discovered in 1839 by a 19-year-old French physicist, Edmund Becquerel, who observed that a photocurrent would flow between two electrodes in a solution when the apparatus was exposed to light [42], [43]. Almost 40 years later, the effect was noticed in selenium by William Adams and Richard Day, and the first solid-state solar cells were made from selenium by Charles Fritts and Werner Siemens. However, many investigators were sceptical about these devices because the quantum physics required to explain the observed effect were not known yet. It was not until Max Planck's proposal of the quantum nature of light in 1900 that the theoretical foundations for understanding PV were established. They were able to build cells made of selenium that were 1% to 2% efficient. Selenium cells were quickly adopted by the emerging photography industry for photometric light meters. As part of his development of quantum theory, Albert Einstein published a theoretical explanation of the photovoltaic effect in 1904, which led to a Nobel Prize in 1923 [42]. About the same time, in what would turn out to be a cornerstone of modern electronics in general, and photovoltaics in particular, a Polish scientist by the name of Czochralski began to develop a method to grow perfect crystals of silicon. By the 1940s and 1950s, the Czochralski process began to be used to make the first generation of single-crystal silicon photovoltaics, and that technique continues to dominate the photovoltaic (PV) industry today [42]. Then, in 1954, Calvin Fuller and Gerald Pearson were working on new silicon rectifier diode technology at Bell Laboratories, and during one experiment they found that their device produced a significant photocurrent when strongly illuminated [43]. At that same time, Daryl Chapin was working on selenium solar cells. When Pearson alerted Chapin to his silicon discovery, Chapin immediately abandoned his selenium work and switched to silicon, and after significant effort but a relatively short time, the result was the achievement of 6% conversion efficiency. However, the energy cost for PV, which is the critical figure of merit for PV systems (usually expressed in $/kWh), was nearly a thousand times that of competing alternatives at that time. Although technically successful, PV was still too expensive to be useful. Surprisingly, the study records that solar cells, also called photovoltaic (PV) cells, were developed by Carlson and Wronski in 1976 [18].

But as long as 120 years ago, visionaries looking through the soot and smoke of the early industrialising world saw the need for a renewable and environmentally acceptable energy source [44]. Writing in 1891, Appleyard foresaw "the blessed vision of the Sun, no longer pouring his energies unrequited into space, but, by means of photo-electric cells and thermo-piles, these powers gathered into electrical storehouses to the total extinction of steam engines, and the utter repression of smoke." It is interesting to note Appleyard's specific mention of what he calls photo-electric cells. This energy conversion approach was known even then due to Becquerel's discovery of photovoltaic action in 1839.

2.3.1.2 Photovoltaic Energy Conversion

Photovoltaic energy conversion is the direct production of electrical energy in the form of current and voltage from electromagnetic (i.e., light, including infrared, visible, and ultraviolet) energy [44]. A solar cell is a large-area semiconductor diode [45]. It consists of a *p-n* junction created by an impurity addition (doping) into the semiconductor crystal (consisting of four covalent bonds to the neighboring atoms for the most commonly used silicon solar cells). Semiconductor materials have bands of allowed and forbidden energy in their spectrum of electronic energy (the energy gap) [35]. Inside the allowed band, there are valence and conduction bands, separated by such an energy gap. The electrons occupy the valence band and can be excited in the conduction band by thermal energy or by absorption of photons with energy quantum higher than the energy gap. The bandwidth of the energy gap is characteristic for each semiconductor. So, when an electron passes from one band to other, it leaves in its place a hole that can be considered a positive charge. When voltage is applied across the semiconductor, the electrons and their holes contribute to the electrical current, since the presence of that electric field makes those particles move in opposite directions with respect to each other. Therefore, an electrostatic potential inside the material is created to separate positive from negative charges. Whenever the semiconductor is illuminated, it behaves like a battery; in other words, the charges accumulate in opposite areas of the chip. When a load is applied, a current flow through it and electrical power is dissipated as shown in Figure 2.1 [46].

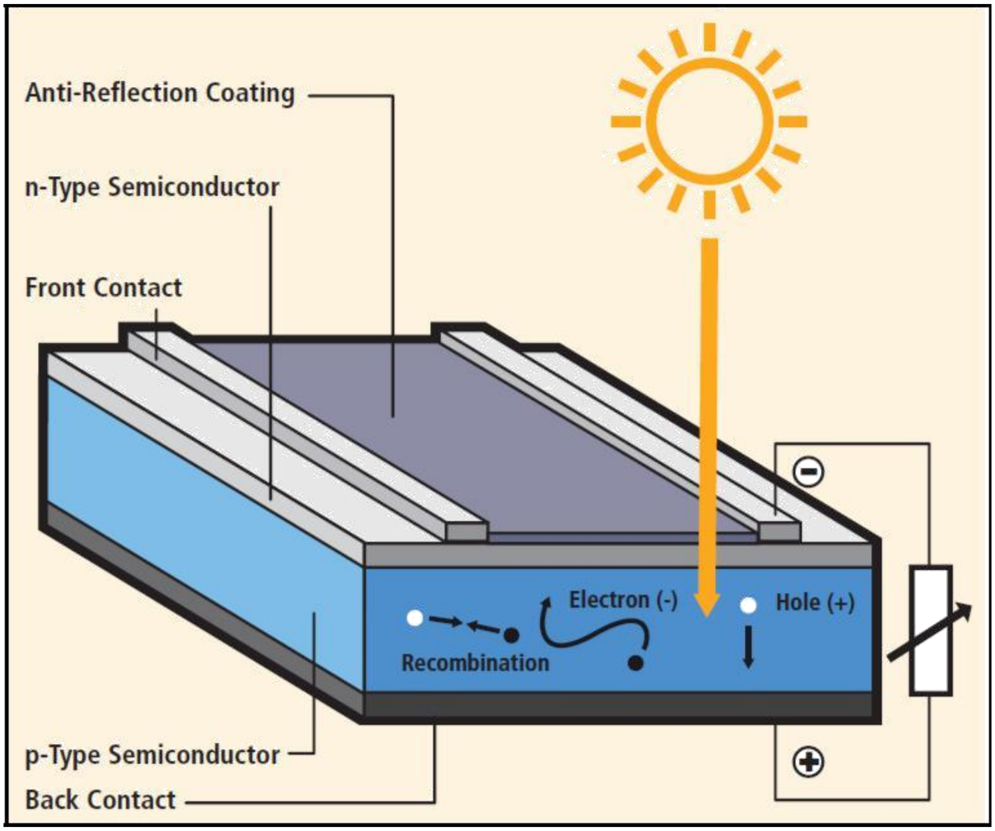


Figure 2.1: Generic schematic cross-section illustrating the operation of an illuminated solar cell

There are four steps needed for photovoltaic energy conversion are [44]:

- a light absorption process which causes a transition in a material (the absorber) from a ground state to an excited state,

- the conversion of the excited state into (at least) a free negative- and a free positive-charge carrier pair, and
- a discriminating transport mechanism, which causes the resulting free negative-charge carriers to move in one direction (to a contact that we will call the cathode) and the resulting free positive-charge carriers to move in another direction (to a contact that we will call the anode).

The energetic, photo generated negative-charge carriers arriving at the cathode result in electrons which travel through an external path (an electric circuit). While traveling this path, they lose their energy doing something useful at an electrical "load," and finally they return to the anode of the cell. At the anode, every one of the returning electrons completes the fourth step of photovoltaic energy conversion, which is closing the circle by combining with an arriving positive-charge carrier, thereby returning the absorber to the ground state.

In some materials, the excited state may be a photogenerated free electron– free hole pair. In such a situation, step 1 and step 2 coalesce. In some materials, the excited state may be an exciton, in which case steps 1 and 2 are distinct.

This "photovoltaic" effect requires no moving parts and does not use up any of the material in the process of generating electricity [37]. The most attractive features of solar panels are the nonexistence of movable parts, very slow degradation of the sealed solar cells, flexibility in the association of modules (from a few watts to megawatts), and the extreme simplicity of its use and maintenance [35]. As shown in Figure 2.2, a typical solar cell consists of a glass or plastic cover or other encapsulant, an antireflective surface layer, a front contact to allow electrons to enter a circuit, a back contact to allow the electrons to complete the circuit, and the semiconductor layers where the electrons begin and complete their journey.

2.3.1.3 Classification of Photovoltaic

There are a number of ways to categorize photovoltaics based mainly on the different types of technologies currently used to manufacture them. One dichotomy is based on the thickness of the semiconductor. Conventional crystalline silicon solar cells are, relatively speaking, very thick – of the order of 200–500μm [42]. An alternative approach to PV fabrication is based on thin films of semiconductor, where "thin" means something like 1–10μm. Thin-film cells require much less semiconductor material and are easier to manufacture, so they have the potential to be cheaper than thick cells. The first generation of thin-film PVs were only about half as efficient as conventional thick silicon cells; they were less reliable over time, yet they were no cheaper per watt, so they really weren't competitive. Currently, however, about 80% of all photovoltaics are thick cells and the remaining 20% are thin-film cells used mostly in calculators, watches, and other consumer electronics.

The so-called 1st generation of solar cells based on e.g. bulk crystalline and polycrystalline silicon is still dominating the PV market [47]. However, so-called 2nd generation solar cells mainly consisting out of thin film solar cells based on CdTe, Copper Indium Gallium Selenide (CIGS), and amorphous silicon has currently gained distribution of 25% in market share worldwide. It is expected that this number will increase significantly within the next years. While for the 1st and 2nd generation solar cells commercial solar panels are available with decent power conversion efficiencies (PCEs) and lifetimes, the emerging 3rd generation solar cells such as OPV (organic PV) and DSSCs (dye-sensitized solar cells) technologies are still in the development phase. It is in agreement with [47] that these emerging PV technologies are still under development [46] and in laboratory or (pre-) pilot stage, but could become commercially viable within the next decade. According to [46], they are based on very low-cost materials and/or processes and include technologies such as dye-sensitized solar cells, organic solar cells and low-cost (printed) versions of existing inorganic thin-film technologies. However, contrary to the position of [46] on the commercial viability of these emerging PV technologies, [47] assert that some commercially available products have recently entered the market such as e.g. solar bags representing niche products, which are so far not suitable for competing with traditional large scale applications of solar panels of the 1st and 2nd generations. In traditional solar panels the differences between best solar cell and average solar cell efficiencies are much smaller than for the emerging solar cell technologies with the consequence that modules of 3rd generation solar cells still suffer from very low performance.

Photovoltaic technologies can also be categorized by the extent to which atoms bond with each other in individual crystals as follows [36], [42]

- *single crystal* , the dominant silicon technology;
- *multicrystalline*, in which the cell is made up of a number of relatively large areas of single crystal grains, each on the order of 1 mm to 10 cm in size, including multicrystalline silicon (mc-Si);
- *polycrystalline*, with many grains having dimensions of the order of 1 μm to 1 mm, as is the case for cadmium telluride (CdTe) cells, copper indium diselenide (CuInSe2,) and polycrystalline, thin-film silicon;
- *microcrystalline* cells with grain sizes less than 1 μm; and
- *amorphous*, in which there are no single-crystal regions, as in amorphous silicon (a-Si).

Another way to categorize photovoltaic materials is based on whether the *p* and *n* regions of the semiconductor are made of the same material (with different dopings, of course)—for example, silicon. These are called *homojunction* photovoltaics. When the *p*–*n* junction is formed between two different semiconductors, they are called *heterojunction* PVs.

PVs are capable of converting incident solar energy into dc current, with efficiencies varying from 3 to 31%, depending on the technology, the light spectrum, temperature, design, and the material of the solar cell [35]. Therefore, they have compared the performances of the commonest materials used in PV modules for certain sizes as depicted in Table 2.5.

Table 2.5: Commonest Materials Used in PV Modules [35]

Type	Theoretical Efficiency		Practical Tests	Modules	
	cm^2	η (%)	η (%)	cm^2	η (%)
Monocrystalline silicon (Si)	4	29	23	100	15-18
Polycrystalline silicon (Si)	4	---	18	100	12-18
Amorphous silicon (a-Si)	1	27	12	1000	5-8
Gallium arsenide (GaAs)	0.25	31	26	---	---
Copper indium-selenide (CIS)	3.5	27	17	---	---
Cadmium telluride (CdTe)	1	31	16	---	---

Similarly [47] have extended the power conversion efficiency (PCE) comparison to include the 3rd generation PVs as shown in Table 2.6. According to them it should be noted that especially for the emerging new PV technologies the average efficiencies are significantly lower than the results of the best cells.

Table 2.6: Comparison of best and average PCE values of single solar cells and modules of different PV technologies [47]

PV Technology	Best cell PCEs	Average cell PCEs	Best module PCEs	Average module PCEs
Si (bulk)	25.0% (mono-crystalline)		22.9% (mono-crystalline)	14 – 17.5% (mono-crystalline)
	20.4% (poly-crystalline)	---	17.55% (poly-crystalline)	13 – 15% (poly-crystalline)
	10.1% (amorphous)			5 – 7 % (amorphous)
CIGS (thin film)	20.3%	---	15.7%	10 – 14%
CdTe (thin film)	16.7%	---	10.9%	~ 10%
DSSC	11.2	5 – 9%	5.38%	---
OPV (thin film)	8.3% and 8.5%	3 – 5%	3.86%	1 – 3%

Cells are the building block of PV systems and a silicon cell produces 0.5 volts [48]. Since an individual cell produces only about 0.5 V, it is a rare application for which just a single cell is of any use. Instead, the basic building block for PV applications is a *module* consisting of a number of pre-wired cells in series, all encased in tough, weather-resistant packages [42]. Multiple modules, in turn, can be wired in series to increase voltage and in parallel to increase current, the product of which is power. Such combinations of modules are referred to as an *array*. Figure 2.4 shows this distinction between cells, modules, and arrays.

2.3.1.4 Grid Connection of Photovoltaic Systems

As stated in the preceding section, the basic elements of a PV system are the modules that are usually series-connected and a series of PV modules is usually called a PV string. But several components are needed to construct a grid connected PV system to perform the power generation and conversion functions, as shown in Figure 2.2. Depending on the number of the modules, the PV array converts the solar irradiation into specific DC current and voltage [49], [50].

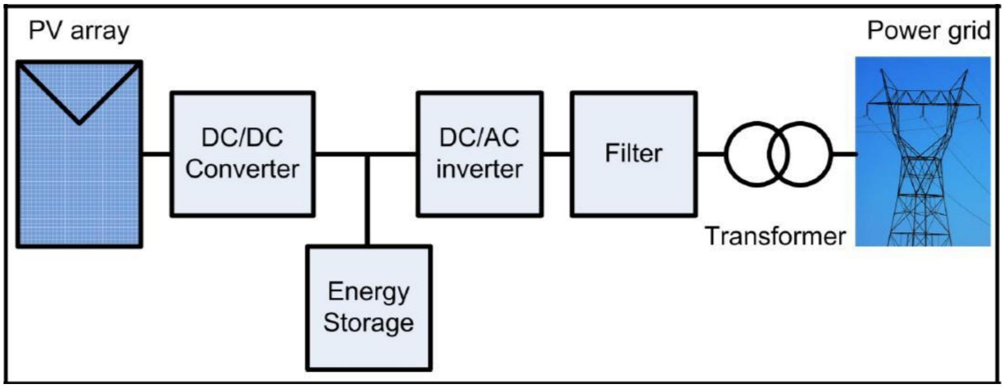


Figure 2.2: **Components of a grid connected PV system**

If the voltage of the PV string is always higher than the peak voltage of the grid the PV converter does not require a step-up stage [51]. In this case higher efficiency can be obtained because a single stage full-bridge converter can be used. Otherwise, a DC-DC boost converter or a transformer must be added for voltage amplification but it reduces efficiency. However, energy storage devices can be included in order to store the energy produced in case of grid support connection [50], [49]. A three-phase inverter performs the power conversion of the array output power into AC power suitable for injection into the grid. Pulse width modulation control is one of the techniques used to shape the magnitude and phase of the inverter output voltage.

The PV inverter is the key element of grid-connected PV power systems and the main function is to convert the DC power generated by PV panels into grid-synchronized AC power. High frequency harmonics in the output current due to power semiconductors switching are reduced by the filter. An interfacing transformer is connected after the filter to step up the output AC voltage of the inverter to match the grid voltage level. The power transformer is used only for galvanic isolation between the PV system and the utility grid [49]. [50] adds that protection relays and circuit breakers are used to isolate the PV system when faults occur to prevent damage to the equipment if their ratings are exceeded. Therefore, according to [51] a PV system is the combination of PV fields and the related power converters.

Historically the first grid-connected PV plants were introduced in the 1980s as thyristor-based central inverters [52]. According to them, the first series-produced transistor-based PV inverter was PV-WR in 1990 by SMA. Moreover, since the mid 1990s, IGBT and MOSFET technology has been extensively used for all types of PV inverters except module-integrated ones, where MOSFET technology is dominating.

2.3.2 Wind Energy System

Wind energy relies, indirectly, on the energy of the sun. A small proportion of the solar radiation received by the Earth is converted into kinetic energy, the main cause of which is the imbalance between the net outgoing radiation at high latitudes and the net incoming radiation at low latitudes [46]. The Earth's rotation, geographic features and temperature gradients affect the location and nature of the resulting winds [53]. The use of wind energy requires that the kinetic energy of moving air be converted to useful energy. As a result, the economics of using wind for electricity supply are highly sensitive to local wind conditions and the ability of wind turbines to reliably extract energy over a wide range of typical wind speeds. According to [54] wind power deployment has more than doubled since 2008, approaching 300GW of cumulative installed capacities, led by China (75GW), the United States (60GW) and Germany (31GW). Wind power now provides 2.5% of global electricity demand – and up to 30% in Denmark, 20% in Portugal and 18% in Spain. Its roadmap targets 15% to 18% share of global electricity from wind power by 2050, a notable increase from the 12% aimed for in 2009. It has therefore set a new target of 2 300GW to 2 800GW of installed wind capacity will avoid emissions of up to 4.8 Gt of CO_2 per year.

2.3.2.1 Modern Wind Turbine

According to [55], the beginning of modern wind turbine development was in 1957, marked by the Danish engineer Johannes Juul and his pioneer work at a power utility (SEAS at Gedser coast in the Southern part of Denmark). His R&D effort formed the basis for the design of a modern AC wind turbine – the well-known Gedser machine which was successfully installed in 1959. With its 200kW capacity, the Gedser wind turbine was the largest of its kind in the world at that time and it was in operation for 11 years without maintenance. The robust Gedser wind turbine was a technological innovation as it became the hall mark of modern design of wind turbines with three wings, tip brakes, self-regulating and an asynchronous motor as generator. Foreign engineers named the Gedser wind turbine as 'The Danish Concept'. The so-called "Danish concept" that was very popular in the eighties, refers to the transformation of wind energy into electrical energy using a simple squirrel-cage induction machine directly connected to a three-phase power grid [56].

Wind turbines come in two broad categories: the horizontal-axis turbine whose blades appear similar to aeroplane propellers, and the vertical-axis turbine whose long curved blades are attached to the rotor tower at the top and bottom and have the appearance of an eggbeater [57]. Vertical-axis turbines have not lived up to their early promise, and today virtually 100 per cent of existing turbines use the horizontal-axis concept.

Figure 2.3 [46] shows the components in a modern wind turbine with a gearbox; in wind turbines without a gearbox, the rotor is mounted directly on the generator shaft. The rotor is the heart of a wind turbine and consists of multiple rotor blades attached to a hub [55]. It is the turbine component responsible for collecting the energy present in the wind and transforming this energy into mechanical motion.

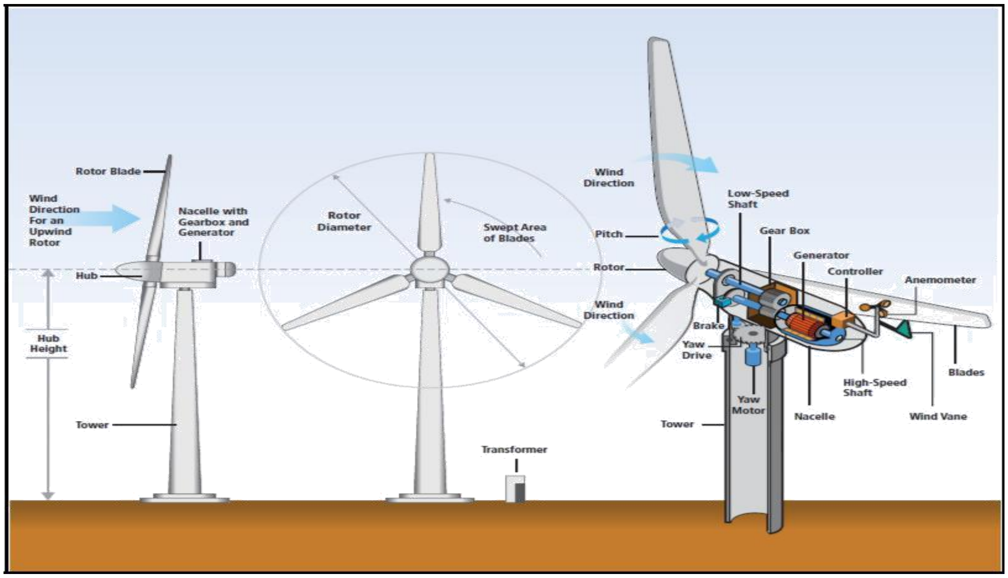


Figure 2.3: **Basic components of a modern, horizontal-axis wind turbine with a gearbox**

Modern wind turbines, which are currently being deployed around the world, have three-bladed rotors with diameters of 70m to 80m mounted atop 60m to 80m towers [58], as illustrated in Figure 2.13. But according to [55], currently most rotors have three blades, a horizontal axis, and a diameter of between 40 and 90 meters. In addition to the currently popular three-blade rotor, two-blade rotors are also used to be common in addition to rotors with many blades, such as the traditional wind mills with 20 to 30 metal blades that pump water. They have also noted that over time, it was found that three-blade rotor is the most efficient for power generation by large wind turbines. In addition, the use of three rotor blades allows for a better distribution of mass, which makes rotation smoother and also provides for a "calmer" appearance.

The three blades are attached to a hub and main shaft, from which power is transferred (sometimes through a gearbox, depending on design) to a generator. The main shaft and main bearings, gearbox, generator and control system are contained within a housing called the nacelle. Typical power output versus wind speed curve is shown in Figure 2.4 [46], [58]

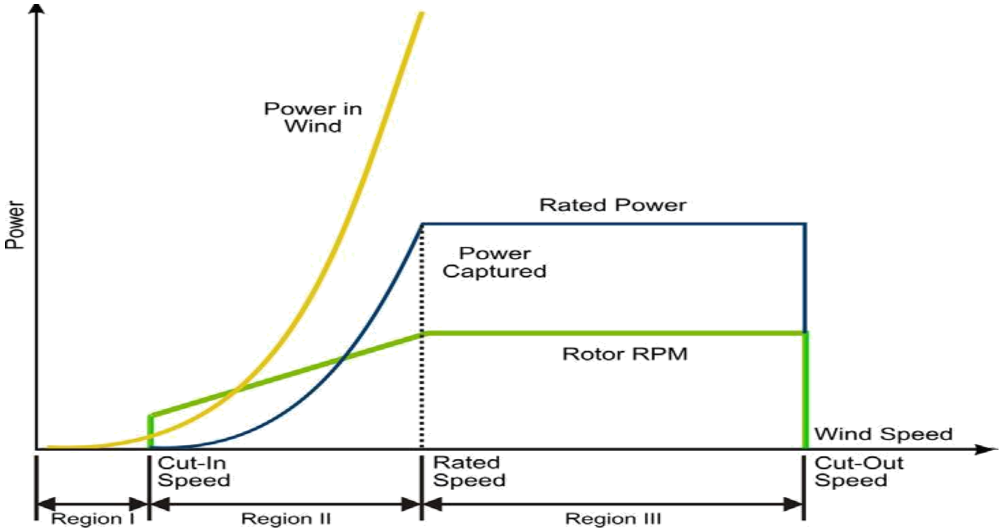


Figure 2.4: Typical power output versus wind speed curve

2.4 Conclusion

This chapter has reviewed the various definitions of DG and its two typical technology examples. This has shown that irrespective of its various terms or definitions DG is a fairly new concept in the economics literature about electricity markets, but the idea behind it is not new at all. Basically the different terms often refer to different aspects or properties of the new types of generation. Also there is a strong overlap between the terms, but there are some serious differences as well. Therefore, in this work the term “distributed generation” refers to production units connected to the distribution network especially production units based on renewable energy sources.

From Section 1.1, the two main reasons necessitating South Africa’s deployment of renewable DG are CO_2 emission curtailment and improvement of Eskom’s wafer thin reserve margin. These are achievable by increasing the attention accorded CSP, if not bringing it at par with wind and PV, given the country’s impressive DNI although renewable energy electricity generation is not absolutely “zero-emission”. Unfortunately, South Africa’s electricity network was not designed for this kind of generation. Therefore, appropriate questions to ponder about are the probable consequences of the integration of this “new” type of generation and this is the focus of next chapter.

CHAPTER 3

3. DISTRIBUTED GENERATION INTEGRATION ISSUES

3.1 Introduction

The aim of this chapter is to review the inherent issues of DG integration. It begins with a deeper consideration of the DG renaissance. Thereafter the threat or challenges posed by DG integration will be highlighted.

3.2 Distributed Generation Renaissance

A lot has been written concerning the rebirth of DG. Some of the reasons adduced are location or region based for instance electricity generation issues in OECD countries are different from BRICS countries. According to [59], the impending deregulated environment faced by the electric utility industry and recent advances in technology, several DG options are fast becoming economically viable. They have listed a multitude of recent events that have created a new environment for the electric power infrastructure leading to an upsurge in interest in the development and utilization of DG as follows:

- Deregulation of the electric utility industry and the ensuing breakup of the vertically integrated utility structure.
- Public opposition to building new transmission lines on environmental grounds.
- Keen public awareness of the environmental impacts of electric power generation.
- Rapid increases in electric power demand in certain regions of the country.
- Significant advances in several generation technologies that are much more environmentally benign (wind-electric generation, micro turbines, fuel cells, and photovoltaics) than conventional coal, oil, and gas-fired plants.
- Increasing public desire to promote "green" technologies based on renewable energy sources.
- Awareness of the potential of DG to enhance the security of electric power supply, especially to critical loads, by creating mini- and micro-grids in the case of emergencies and/or terrorist acts, and/or embargoes of energy supplies.

While commenting on the value of distributed generation [60] have noted that where there is no power, any source of power generation is, of course, of significant value to the end-user, to the regional government, and to the prospective energy service company. According to them, from the electricity industry perspective, DG is attractive because it has multiple other values which include the following:

- The generator can be sited close to the end-user, thus decreasing transmission and distribution costs and electrical losses.
- Sites for small generators are easier to find.
- Distributed generators offer reduced planning and installation time.
- Because the DG units are distributed, the "system" may be more reliable. One unit can be removed for maintenance or service with only a moderate effect on the rest of the power distribution system. This is especially important for new technologies where the long-term reliability is not proven.
- Newer distributed generation technologies offer an environmentally clean and low noise source of power.
- Newer distributed generators can run on multiple types of fuels. This allows flexibility and reduction in cost of the infrastructure required to get the fuel to the generator. The preferred fuel source differs in various parts of the world. However, the required quality of the selected fuel may be more important for certain new DG technologies.
- Newer distributed generators can run on fuels generated from bio gasification. Biomass (e.g., wood, hog waste, agricultural byproducts) is a truly renewable source of fuel in most developing countries and especially in agricultural regions.

Equally from the end-user perspective, DG is also attractive for several reasons such as:

- Power is readily available and the power has improved quality and reliability over power produced from central generating stations.
- Depending on the nature of fuel used, electricity prices are often lower than power from central plants.
- Some DG technologies provide cogeneration possibilities, which allow site recovery of heat and / or hot water. This has the potential to raise energy efficiency to around 90%. In rural villages, the recovered heat can be used for hot water, space heating, industrial processes and even space cooling (adsorption air conditioners)

A research [59], posit that the key element of this new environment is to build and operate several DG units near load centres instead of expanding the central-station power plants located far away from customers to meet increasing load demand. Therefore, according to [17], the overall trend is concerned with efficient utilisation of DG in:

- supplying electricity to small loads in remote locations where it may be more economic than establishing a new line to the load site;
- supplying heat energy and steam to hospitals and some industries from cogeneration systems;
- providing high power quality for electronic and sensitive equipment;
- backup power source during utility outages, in particular, for loads requiring uninterrupted power supply such as hospitals, banks, and data centers;
- peak-shaving programs where DG can be used during high - cost periods to supply consumers participating in the programs resulting in reduction of overall power cost;
- reduction of air emissions by using renewable energy sources;
- avoiding distribution system investments;
- providing excess capacity to utilities;
- dispatching DG to achieve most economical operation taking into account the priority of supplying independent producers; and
- reducing transmission and distribution (T & D) losses.

Most of the benefits of employing DG in existing distribution networks have both economic and technical implications and they are interrelated [59]. While all the benefits can be ultimately valuated in terms of money, some of them have a strong technical flavour than others. As such, they have proposed to classify the benefits into two groups – technical and economic. The major technical benefits are:

- ➢ reduced line losses;
- ➢ voltage profile improvement;
- ➢ reduced emissions of pollutants;
- ➢ increased overall energy efficiency;
- ➢ enhanced system reliability and security;
- ➢ improved power quality;
- ➢ relieved transmission and distribution congestion.

Also the major economic benefits are:

- ➢ deferred investments for upgrades of facilities;
- ➢ reduced operation and maintenance costs of some DG technologies;
- ➢ enhanced productivity;
- ➢ reduced health care costs due to improved environment;
- ➢ reduced fuel costs due to increased overall efficiency;
- ➢ reduced reserve requirements and the associated costs;
- ➢ lower operating costs due to peak shaving; and
- ➢ increased security for critical loads.

These benefits are deemed as the positive impacts. However, distributed energy resources add new challenges to the distribution system design process in the areas of safety, fault sensing, and protection, among others. This is because traditionally the distribution network is designed and operated assuming that the electricity is brought in from the Grid Supply Point [61]. The specifications of network components of both plant gears and control gears and operation arrangements are therefore based on this assumption. The penetration of distributed generators into distribution network voids the conditions on which the network designs and operations are based. Consequently, distribution-system engineers are currently divided between DG advocates and adversaries, each having their own valid reasons [62]. One of the main reasons for this conflict is just "fear of what could happen" due to the lack of practical knowledge on traditional power systems having a high level of DG penetration. According to them, still fresh in the minds of many engineers is the wrong approach that has been taken in the past by large computer manufacturers when they underestimated the growing market of personal computers; an analogy with the present DG situation that is easy to make.

There are concerns about the compliance of the generator connection with the standards and practices of network design and operation. The requirements (and, therefore, the complexity and cost) of protection and control systems for distributed resource systems, beyond the requirements of various standards, codes, and required certifications, depend primarily on [22]:

- The size of the DG system with respect to the minimum total customer load on the feeder
- The number, size, and location of other DG units on the feeder
- The purpose of the DG — grid-connected or primarily grid-independent operating mode
- The type of DG — diesel generator, gas turbine generator, fuel cell, etc.
- The specific configuration of the feeder system (including laterals to the loads), including the size, location, operating mode, type of relays, breakers, and fuses, the feeder voltage, and the location, size, and configuration of all transformers
- Network operator requirements specific to that network (possibly as a result of experience with unique and unusual loads) and any additional safety requirements of local jurisdictions
- The DG penetration level, and
- The strength of the system at the point of DG connection.

3.3 Distributed Generation Integration

In considering the positive and negative impacts of distributed generation it could be proper to ask "Is it *integration* or *interconnection* of distributed generation?" This appears crucial because of their interchangeability by some authors while some maintain their individuality. According to Basso, the interconnection in IEEE 1547 is defined as "the result of the process of adding a DR unit to an area EPS (electric power system)" [63]. A technical barrier to the interconnection of DR is its effect on the area EPS – referred to as system impacts. Interconnection is a widely known concept and the fundamental area covered by the IEEE 1547 series of standards [64]. He has noted that generally it deals with all equipment and functions used to interconnect a distributed energy resource unit with an area electric power system (distribution system).

Integration specifically means the physical connection of the generator to the network with due regard to the secure and safe operation of the system and the control of the generator so that the energy resource is exploited optimally [15]. They maintain that proper integration of any electrical generator into an electrical power system requires knowledge of the well-established principles of electrical engineering. Also the integration of generators powered from renewable energy sources is fundamentally similar to that of fossil fuelled powered generators and is based on the same principles, but, renewable energy sources are often variable and geographically dispersed. It asserts that the term "integration" is much broader than simply the interconnection of DR, because integration considers the entire electric power system and how DR influences it. Consequently, it posits that there are three key elements associated with integration of DR into the electric power system namely:

- Interconnection practices
- System design and operation impacts
- Communications and control possibilities

Interconnection practices are those matters dealing with the types of control relays, transformer interfaces, disconnect switches, and other-site specific DR hardware required for successful operation of the DR. *System design and operation impacts* deal with the broader scope of how the electric power system is affected by the DR. This includes impacts such as voltage regulation, flicker, harmonics, and reliability. These types of impacts may involve studies such as load flow, harmonic, and short-circuit analysis. *Communication and control possibilities* address the need for data and control signals to be transferred to and from DR equipment to other electric power system equipment and/or control centers as is required for safe and effective operation of DR.

It further notes that it is important to recognize that all three of these areas are closely inter-related. For example, the voltage impacts of DR on the power system are influenced by DR interconnection practice and the controls employed.

From the forgoing and given definition of interconnection on the study "IEEE Standard for Interconnecting Distributed Resources with Electric Power System" as the result of the process of adding a DR unit to an Area EPS, it may be proper to conclude by concurring that interconnection is a subset of integration: an analogue to DER and DG. Therefore, interconnection and integration could be accorded a cause-effect relationship.

3.3.1 Distributed Generation Interfaces

Interfaces are the point of interaction between DG and the energy infrastructure as shown in Figure 3.1. The physical interfaces include a DG unit's interaction with the fuel and electrical infrastructure. Physical interfaces are mainly concerned with issues such as safety, protocols, system impacts, reliability, standards, and metering. Some forms of DG will involve a communications interface with a central entity that controls and/or monitors the DG system. The market interface covers how the DG unit or its owner interacts or competes with other suppliers in the marketplace. The market interface includes concerns over dispatch, tariffs, pricing signals, response, and business and operational decisions. Distributed generation interfaces are shown in Figure 3.1 [65]

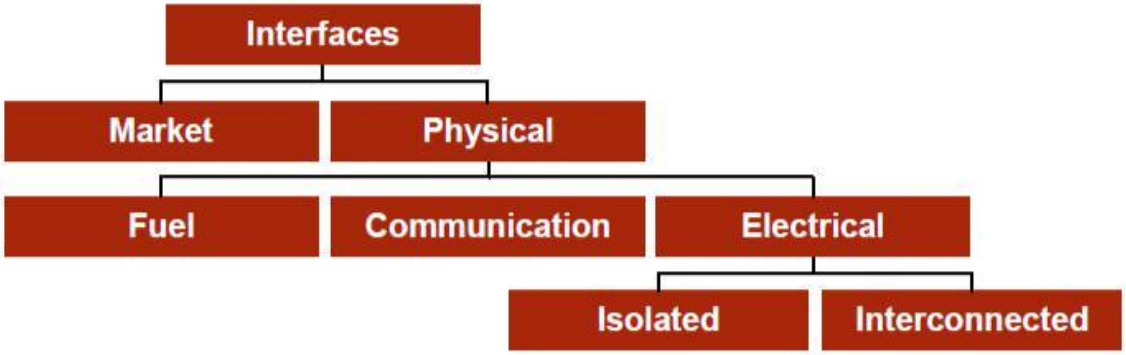


Figure 3.1: **Distributed generation interfaces**

A. D. Little has noted that while there are issues surrounding all of these interfaces, the most important issues in the short term are on the electrical interface [65]. Also that the most contentious issues in the electrical interface are those involving DG interconnected to the grid.

The electric power system interface is the means by which the DG unit electrically connects to the power system outside the facility in which the unit is installed. A. D. Little asserts that depending on the application and operation of the DG unit, the interface configuration can range from a complex parallel interconnection, to being non-existent if the DG unit is operated in isolation [65]. Therefore, the electrical interface determines the status of the DG as either grid-connected or standalone (isolated). However, the complexity of the interface increases with the level of interaction required between the DG unit/owner and the electrical grid/distribution company.

Grid interconnection is the most complex electrical interface configuration and the source of many issues involving DG. For most customers, DG systems are most cost-effective and efficient when they are interconnected with the utility grid [66]. According to them, in simple terms, "interconnected with the grid" means that both the DG system and the grid supply power to the facility at the same time. Paralleled systems offer added reliability, because when the DG system is down for maintenance, the grid meets the full electrical load, and vice versa. The term "interconnection" is often used synonymously with the terms "synchronized operation" or "parallel operation" [65]. In this configuration, the DG unit is connected to the electric grid system while it generates electricity.

Consequently, distributed generation systems can be designed to keep a facility up and running without an interruption if the grid experiences an outage. Also grid-interconnected systems can be sized smaller to meet the customer's base load as opposed to its peak load. Not only is the smaller base-load system cheaper, it also runs closer to its rated capacity and, therefore, is more fuel efficient and cost-effective. Therefore, they believe that two different types of grid interconnection are possible: parallel or roll-over. With the parallel operation, the DG system and the grid are interconnected and both are connected to the load. In the rollover operation, the two sources are interconnected, but only one is connected with the load. In their view a typical interconnection system includes three kinds of equipment:

- Control equipment for regulating the output of the DG
- A switch and circuit breaker (including a "visible open") to isolate the DG unit
- Protective relaying mechanisms to monitor system conditions and to prevent dangerous operating conditions.

3.3.2 Impacts of Distributed Generation

While discussing the reasons for the resurgence of distributed generation in Section 3.2, those advantages or benefits of DG were deemed as the positive impacts. That was quickly and briefly followed by the disadvantages because of the divergent views of its proponents and opponents. Consequently, the focus of this section is on some of the negative effects of DG integration.

Firstly, the following impacts are some of the major “planning and design” concerns of utilities when DG is interconnected to the grids [67].

- Harmonic distortion
- Loading concerns
- Voltage flicker
- Voltage regulation

But according to [68] large scale integration of DG units in the distribution grid not only affects the grid planning but also has an impact on the operation of the to integrate DER, increasing subsidies for DSM and direct metering of DER will result in the potential for a squeeze on profitability and, thus, credit metrics. While the regulatory process is expected to allow for recovery of lost revenues in future rate cases, tariff structures in most places call for non-DER customers to pay for (or absorb) lost revenues. As DER penetration increases, there is a cost-recovery structure that will lead to political pressure to undo these cross subsidies and may result in utility stranded cost exposure. Therefore, they posit that aspects which are influenced by the connection of DG units are as follows:

- voltage control;
- power quality;
- protection system;
- fault level; and
- grid losses.

They have also noted that the effect of DG units on these quantities strongly depends on the type of DG unit and the type of the network. Therefore, there are many technical issues that must be considered when connecting a generating scheme to the distribution system, such as [42]:

- thermal rating of equipment
- system fault levels
- stability
- reverse power flow capability of tap-changers
- line-drop compensation
- steady-state voltage rise
- losses
- power quality (such as flicker, harmonics)
- protection.

Some of the problems that may be faced in connecting DG systems to the existing distribution network are technical and some are economical [17]. Therefore, they have noted the technical problems are as follows:

- Some on-load tap changer transformers are not designed for reverse power flow.
- Increase of fault levels.
- Protection of distribution systems is not designed for reverse power flow.
- Nuisance tripping of some healthy parts in distribution systems.
- Existing networks are not designed for high voltage rise. So, voltage reduction schemes and network voltage control schemes are adversely affected by DG, especially if operating under voltage control, or if generator output changes rapidly.
- Metering equipment and communication system between meters and the data centre should be modified.

Some of the distributed generation integration technical problems are highlighted in the following sections beginning with interconnection transformer connections.

3.3.2.1 Interconnection Transformer Connections

Transformer connections play a key role in DR interconnection and the type of winding configuration and connection can affect how the DR impacts the area electric power system [22]. Therefore, understanding distribution transformer characteristics, configurations, and applications is critical to understanding the issues of integrating DR to the system [19]. This is because the vast majority of DR installations involve some sort of existing distribution transformer interface. Unfortunately, many existing distribution transformers are not suitable even for DR applications since the criteria upon which they were originally selected had nothing to do with generation at the customer site. According to [19] many transformer arrangements used in practice are problematic for power flow from the customer system back to the primary.

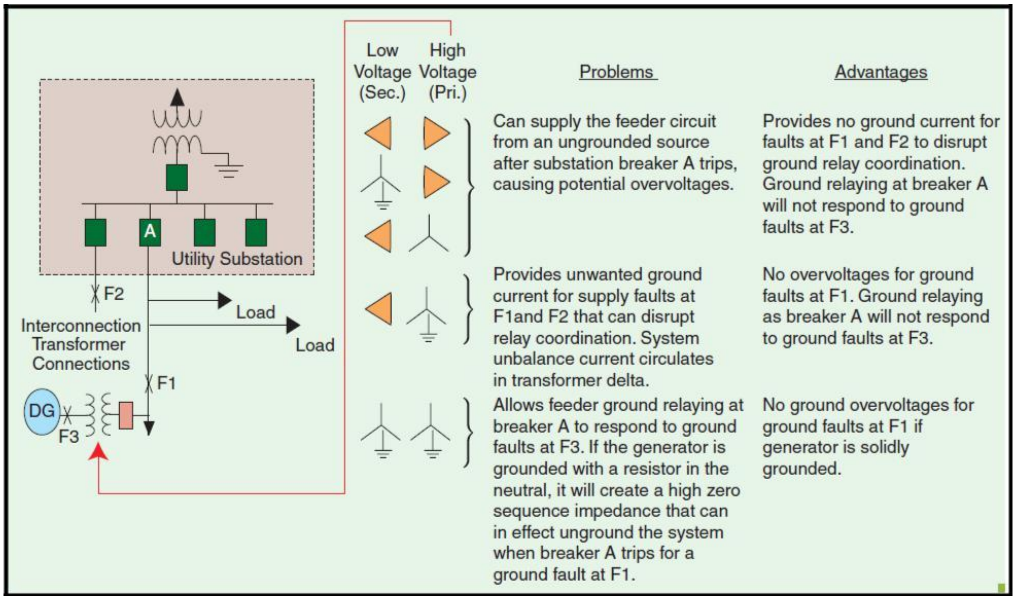
The selection of the interconnection transformer connection has a major impact on how the distributed generator will interact with the utility system and there is no universally accepted "best" connection [22]. However, many utility engineers believe the best transformer connection for DG is grounded wye-delta, with the grounded wye side connected to the utility side, just like central station generation connected to the transmission grid [23]. This is because the protective relaying for this connection is well understood from decades of experience with central station generation and single line-to-ground faults are relatively easy to detect from the phase-to-phase voltages on the DG side. According to them, other fault conditions are also relatively easy to detect. For instance, if the DG accidentally becomes isolated in an island, the utility side still appears to be effectively grounded, although somewhat less so than before the island formed. There are fewer strange resonant conditions that can occur and Ferro resonance is considerably less likely.

Furthermore, they have noted that triple harmonics produced by the machines are blocked by the delta winding (very important for some machines).

The utility and DG owner have only two basic choices in selecting the primary winding configuration of the interconnection transformer [22]:

- Unground primary windings (delta or wye ungrounded) and risk possible over voltages.
- Ground the primary windings (wye grounded) and potentially disrupt feeder relay ground coordination through the injection of unwanted ground current.

Interconnection transformer connections are shown in figure 3.2 [22]



Low Voltage (Sec.)	High Voltage (Pri.)	Problems	Advantages
Δ	Δ	Can supply the feeder circuit from an ungrounded source after substation breaker A trips, causing potential overvoltages.	Provides no ground current for faults at F1 and F2 to disrupt ground relay coordination. Ground relaying at breaker A will not respond to ground faults at F3.
Y⏚	Δ		
Δ	Y		
Δ	Y⏚	Provides unwanted ground current for supply faults at F1and F2 that can disrupt relay coordination. System unbalance current circulates in transformer delta.	No overvoltages for ground faults at F1. Ground relaying as breaker A will not respond to ground faults at F3.
Y⏚	Y⏚	Allows feeder ground relaying at breaker A to respond to ground faults at F3. If the generator is grounded with a resistor in the neutral, it will create a high zero sequence impedance that can in effect unground the system when breaker A trips for a ground fault at F1.	No ground overvoltages for ground faults at F1 if generator is solidly grounded.

Figure 3.2: Interconnection transformer connections

3.3.2.2 Ungrounded Transformer Primary Windings

The three connections under this group are: Delta (HV)/Delta (LV), Delta (HV)/Wye-Gnd (LV) and Wye-Ungnd (HV)/Delta (LV) – High Side Delta or Ungrounded Wye – where (HV) indicates the primary winding and (LV) indicates the secondary winding. According to Mozina (2001) and PSRC (2004) the major concern with these connections is in the area of circuit design, but an advantage of this connection is that there is no source of zero sequence current to impact the utility ground relay coordination. However, coordination problems can arise for fused multiphase laterals and for back feed of phase faults on adjacent feeders.

Referring to Figure 3.3, for ground faults at F1 and F2, all of the fault current will come from the utility. In addition, any ground fault on the secondary of the transformer at F3 will not be detected at the breaker A location. If breaker A is tripped for a ground fault at F1, the utility breaker may trip with the generator still connected and the resulting system is not effectively grounded. This means that with the ungrounded connection, phase faults will have two sources of fault currents. Line to neutral voltages on the unfaulted phases approach the normal line to line voltages which can cause a severe overvoltage of line to neutral connected equipment. If the insulation of the connected equipment has not been selected for those voltage levels, the result will be serious damage to the equipment. The connected distribution transformers will become saturated and damaged, insulators and lightning arrestors will likely flash over and the breaker bushings may fail. It is generally accepted that if the connected generator is rated at less than half of the minimum load on the circuit, it will be unable to sustain more than line to ground voltages. Therefore, they have advised that the ungrounded primary connections should only be considered if the distributed generator is rated at less than half of the load on the circuit. Also, if this type of transformer connection is used, voltage relays must trip the DR for an overvoltage condition. They have noted that minimum load data on a feeder may not be readily available and special data may need to be obtained for this evaluation.

According to [19] DR units using a delta-high-side winding need to include robust anti-islanding protection and fast tripping to help limit the duration of overvoltage problems should they develop.

Many utilities use ungrounded interconnection transformers only if a 200% or more overload on the DG occurs when breaker A trips [22]. During ground faults, this overload level will not allow the voltage on the unfaulted phases to rise higher than the normal line to neutral voltage, avoiding pole-top transformer saturation and potential lightning arrester failure. For this reason, ungrounded primary windings should generally be reserved for smaller DGs, where overloads of at least 200% are expected upon islanding.

3.3.2.3 Grounded Primary Transformer Windings

This consists of Wye-Gnd (HV)/ Delta (LV) – High Side Grounded Wye/Low Side Delta – and Wye-Gnd (HV)/ Wye-Gnd (LV) – Wye-Wye.

According to [69] the Wye-Gnd (HV)/ Delta (LV) establishes a zero sequence current source for ground faults on the distribution system, which could have a significant impact on the utility's ground relay coordination. As Figure 3.4 shows, for a ground fault at F1, the zero sequence fault current will be divided between breaker A location and the grounded neutral of the distributed generator interconnection transformer. The distribution of this fault current will be dependent on the circuit and transformer impedances [69].

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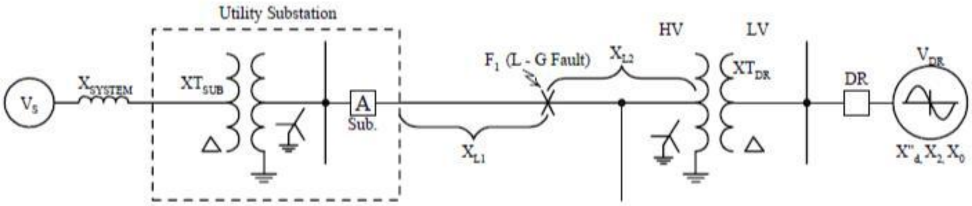


Figure 3.3: **Single-line diagram for Wye-Grounded (HV) / Delta (LV) interconnection transformer**

During serious unbalance conditions such as a blown lateral fuse, the load carrying capability of the interconnection transformer can be reduced [69].

The last interconnection transformer connection to be considered is the Wye-Gnd (HV)/ Wye -Gnd (LV).

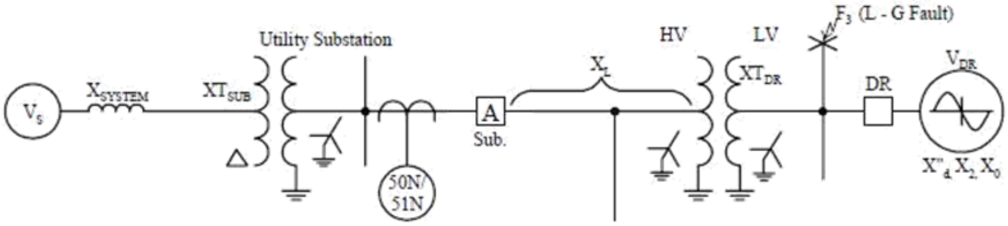


Figure 3.4: **Single-line diagram for Wye-Grounded (HV) / Wye-Grounded (LV) interconnection transformer**

It is the general practice at industrial and commercial medium-voltage facilities to ground generator neutrals with a resistor to limit the ground current between 200 and 400A which causes a large zero sequence impedance [22]. Therefore, he posits that for a permanent feeder supply ground fault (F1), the voltage shift on the unfaulted phase will shift to line to line voltage, similar to an ungrounded primary winding case.

"IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems" in their study addresses the question of over voltages and relay coordination that can be caused by a DG operating in parallel with the utility distribution system with a single sentence that states, “the grounding scheme of the DG interconnection shall not cause over voltages that exceed the rating of the equipment connected to the area electric power system and shall not disrupt the coordination of the ground fault protection on the area electric system” [70]. The considerations to do this are not spelled out in the standard and are a major shortcoming of the document. However, ground concerns are covered in greater depth in the [70] guide.

3.3.2.4 Voltage Rise and Control Due to Distributed Generation

Voltage rise is typically the main constraint for the connection of EGs to LV and MV networks [22]. The main technical barrier to DG on distribution networks has been found to be voltage rise due to significant active power injections from DG. It is mainly an issue on rural networks due to their high impedance and low X/R ratio [22]. This constraint or technical barrier arises because voltage magnitudes at service locations must be maintained within specified ranges. Consequently, to transmit power from an l l kV primary substation to a typical low voltage connected customer some distance away will require the voltage at the primary substation to be higher than the voltage at the point of connection of the customer to the 11 kV systems. The maintenance of system voltages within permitted limits is accomplished in both fixed designs of the system (e.g., conductor selection, substation and distribution transformer tap settings and fixed capacitor banks) and by voltage control equipment such as automatic load tap changers, step-type voltage regulators (SVR), and switched capacitors [22]. According to [22] capacitors (switched and fixed) compensate reactive current, reducing the current from the source to the capacitor location, resulting in reduced line voltage drop. However, capacitors will cause a current increase in feeders if the capacitor size is greater than the load reactive demand due to overcompensation. This will also happen if the capacitor size meets the reactive demand of the total distributed load connected to a feeder, but is installed at a location where it compensates more than the downstream reactive power demand, resulting in voltage increase. But conventional large scale generation which is dispatchable and used for voltage control is being displaced by DG which in many cases is non-dispatchable and does not have voltage control enabled [22]. They have noted that a consequence of this is increasing demand for reactive power at distribution network interfaces, below which DG is connected. Therefore, this new additional reactive power demand is placing a strain on transmission system voltage resources and resulting in lower voltages at times of high DG output.

Interconnection of DG results in changes in power flows and the voltage profile of the feeder, and generally results in over voltages under low load or high (DG) production conditions [22]. According to them in weak networks, the DG capacity is generally determined by the voltage limits. Furthermore, the connection status of a DG is not controlled by the utility. This implies that disconnection of a DG during the high load can cause under voltages, while re-connection of a DG under low load conditions may cause over voltages. Incidentally, this may lead to poor power quality situation and may result in operation of under/over voltage relays.

When a generator is to be connected to the distribution system, the distribution network operator will consider the worst case operating scenarios and ensure that their network and customers will not be adversely affected.

Typically, these scenarios are [42]:

- no generation and maximum system demand
- maximum generation and maximum system demand
- maximum generation and minimum system demand.

3.4 Conclusion

This chapter has reviewed the inherent issues of distributed generation integration commencing with a highlight of DG renaissance. It has shown that DG interconnection and integration and not synonymous though used interchangeably by some authors. Also highlighted in this chapter are some of the technical challenges posed by DG integration.

CHAPTER 4

4. ELECTRICAL GRID CODE Of BANGLADESH

Performance Standards for Transmission

According to the Bangladesh grid code 2012 edition

4.1 Purpose and Scope

- To ensure the quality of electric power in the Grid;
- To ensure that the Grid will be operated in a safe and efficient manner and with a high degree of reliability; and
- To specify safety standards for the protection of personnel in the work environment.

4.2 Power Quality Standards

4.2.1 Power Quality Problems

For the purpose of this Article, Power Quality shall be defined as the quality of the voltage, including its frequency and the resulting current that are measured in the Grid during normal conditions. A Power Quality problem exists when at least one of the following conditions is present and significantly affects the normal operation of the System:

- The System Frequency has deviated from the nominal value of 50 Hz;
- Voltage magnitudes are outside their allowable range of variation;
- Harmonic Frequencies are present in the System;
- There is imbalance in the magnitude of the phase voltages;
- The phase displacement between the voltages is not equal to 120 degrees;
- Voltage Fluctuations cause Flicker that is outside the allowable Flicker Severity limits; or
- High-frequency Over-voltages are present in the Grid.

4.2.2 Frequency Variations

The nominal fundamental frequency shall be 50 Hz.

The control of System frequency shall be the responsibility of the System Operator. The System Operator shall maintain the fundamental frequency within the limits of 49.0 Hz and 51.0 Hz during normal conditions.

4.2.3 Voltage Variations

For the purpose of this Section, Voltage Variation shall be defined as the deviation of the root-mean-square (RMS) value of the voltage from its nominal value, expressed in percent. Voltage Variation will either be of short duration or long duration.

A Short Duration Voltage Variation shall be defined as a variation of the RMS value of the voltage from nominal voltage for a time greater than one-half cycle of the power frequency but not exceeding one minute. A Short Duration Voltage Variation is a Voltage Swell if the RMS value of the voltage increases to between 110 percent and 180 percent of the nominal value. A Short Duration Voltage Variation is a Voltage Sag (or Voltage Dip) if the RMS value of the voltage decreases to between 10 percent and 90 percent of the nominal value.

A Long Duration Voltage Variation shall be defined as a variation of the RMS value of the voltage from nominal voltage for a time greater than one minute. A Long Duration Voltage Variation is an Under-voltage if the RMS value of the voltage is less than or equal to 90 percent of the nominal voltage. A Long Duration Voltage Variation is an Overvoltage if the RMS value of the voltage is greater than or equal to 110 percent of the nominal value.

The Grid Owner and the System Operator shall ensure that the Long Duration Voltage Variations result in RMS values of the voltages that are greater than 95 percent but less than 105 percent of the nominal voltage at any Connection Point during normal conditions.

4.2.4 Harmonics

For the purpose of this Section, Harmonics shall be defined as sinusoidal voltages and currents having frequencies that are integral multiples of the fundamental frequency. The Total Harmonic Distortion (THD) shall be defined as the ratio of the RMS value of the harmonic content to the RMS value of the fundamental quantity, expressed in percent. The Total Demand Distortion (TDD) shall be defined as the ratio of the RMS value of the harmonic content to the RMS value of the rated or maximum fundamental quantity, expressed in percent.

The Total Harmonic Distortion of the voltage and the Total Demand Distortion of the current at any Connection Point shall not exceed the limits given in Tables 4.1 and 4.2, respectively.

Table 4.1: Maximum Harmonic Distortion Factor for Voltage

Harmonic Voltage Distortion			
Voltage Level	THD *	Individual	
		Odd	Even
400 kV	1.5%	1.0%	0.5%
132-230 kV	2.5%	1.5%	1.0%
66 kV	3.0%	2.0%	2.0%

Table 4.2: Maximum Harmonic Distortion Factor for Current

Harmonic Current Distortion			
Voltage Level	THD *	Individual	
		Odd	Even
400 kV	1.5%	1.0%	0.5%
132-230 kV	2.5%	2.0%	0.5%
66 kV	5.0%	4.0%	1.0%

* Total Harmonic Distortion

4.2.5 Voltage Unbalance

For the purpose of this Section, the Negative Sequence Unbalance Factor shall be defined as the ratio of the magnitude of the negative sequence component of the voltages to the magnitude of the positive sequence component of the voltages, expressed in percent. For the purpose of this section, the Zero Sequence Unbalance Factor shall be defined as the ratio of the magnitude of the zero sequence components of the voltages to the magnitude of the positive sequence component of the voltages, expressed in percent.

The maximum Negative Sequence Unbalance Factor at the Connection Point of any User shall not exceed one (1) percent during normal operating conditions.

The maximum Zero Sequence Unbalance Factor at the Connection Point of any User shall not exceed one (1) percent during normal operating conditions.

4.2.6 Voltage Fluctuation and Flicker Severity

For the purpose of this Section, Voltage Fluctuations shall be defined as systematic variations of the voltage envelope or random amplitude changes where the RMS value of the voltage is between 90 percent and 110 percent of the nominal voltage.

For the purpose of this Section, Flicker shall be defined as the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

In the assessment of the disturbance caused by a Flicker source with a short duty cycle, the Short Term Flicker Severity shall be computed over a 10-minute period. In the assessment of the disturbance caused by a Flicker source with a long and variable duty cycle, the Long Term Flicker Severity shall be derived from the Short Term Flicker Severity levels.

The Voltage Fluctuation at any Connection Point with a fluctuating demand shall not exceed one percent (1%) of the nominal voltage for every step change, which may occur repetitively. Any large Voltage Fluctuation other than a step change may be allowed up to a level of three percent (3%) provided that this does not constitute a risk to the Grid or to the System of any User.

The Flicker Severity at any Connection Point in the Grid shall not exceed the values given in Table 4.3.

Table 4.3: **Maximum Flicker Severity**

	Short Term	**Long Term**
132 kV and above	0.8 unit	0.6 unit
below 132 kV	1.0 unit	0.8 unit

4.2.7 Transient Voltage Variation

For the purpose of this Section, Transient Voltages shall be defined as the high-frequency Over-voltages that are generally shorter in duration compared to the Short Duration Voltage Variations. Infrequent short-duration peaks may be permitted to exceed the levels specified in Section 3.2.4 for harmonic distortions provided that such increases do not compromise service to other End-users or cause damage to any Grid equipment. Infrequent short-duration peaks with a maximum value of two (2) percent may be permitted for Voltage Unbalance, subject to the terms of the Connection Agreement or Amended Connection Agreement.

CHAPTER 5

5. DIgSILENT SIMULATION SOFTWARE

5.1 Introduction

DIgSILENT as a software is one of the leaders of the market for years when it comes to grid simulation [71]. DIgSILENT PowerFactory is the most economical solution, as data handling, modelling capabilities and overall functionality replace a set of other software systems, thereby minimizing project execution costs and training requirements. The all-in-one Power Factory solution promotes highly-optimized workflow. DIgSILENT PowerFactory is easy to use and caters for all standard power system analysis needs, including high-end applications in new technologies such as wind power and distributed generation and the handling of very large power systems. In addition to the stand-alone solution, the PowerFactory engine can be smoothly integrated into GIS, DMS and EMS supporting open system standards.

The name DIgSILENT stands for "DIgital SImuLation and Electrical NeTwork calculation program''. PowerFactory, is a powerful calculation program (as written by DIgSILENT) for power system analyses. This a computer aided engineering tool for the analysis of industrial, utility, and commercial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization.

DIgSILENT Version 7 was the world's first power system analysis software with an integrated graphical one-line interface. That interactive one-line diagram included drawing functions, editing capabilities and all relevant static and dynamic calculation features.

PowerFactory 15.2 completes the successful series of PowerFactory version 15 releases. The latest release comes with a broad range of new functions, new electrical models and extensions to the existing modelling suite. Special attention has been paid to improved calculation and simulation performance. Moreover, a variety of new features for improved result visualisation and graphical representation has been made available. With its rich analysis and modelling capabilities, PowerFactory is perfectly suited for network planning and operation studies of increasingly smart grids.

The software by itself provides the ability for simulation of production, transmission and distribution of power through well-defined grid elements. User needs to pick the appropriate elements and assemble a grid model, then there are various options like load flow or short-circuit calculations available. When calculations are over, user can print a report concerning results obtained from calculations. Grid elements available in DIgSILENT are presented in **Figure 5.1**, moreover elements used for modelling in this report are pointed in the same figure.

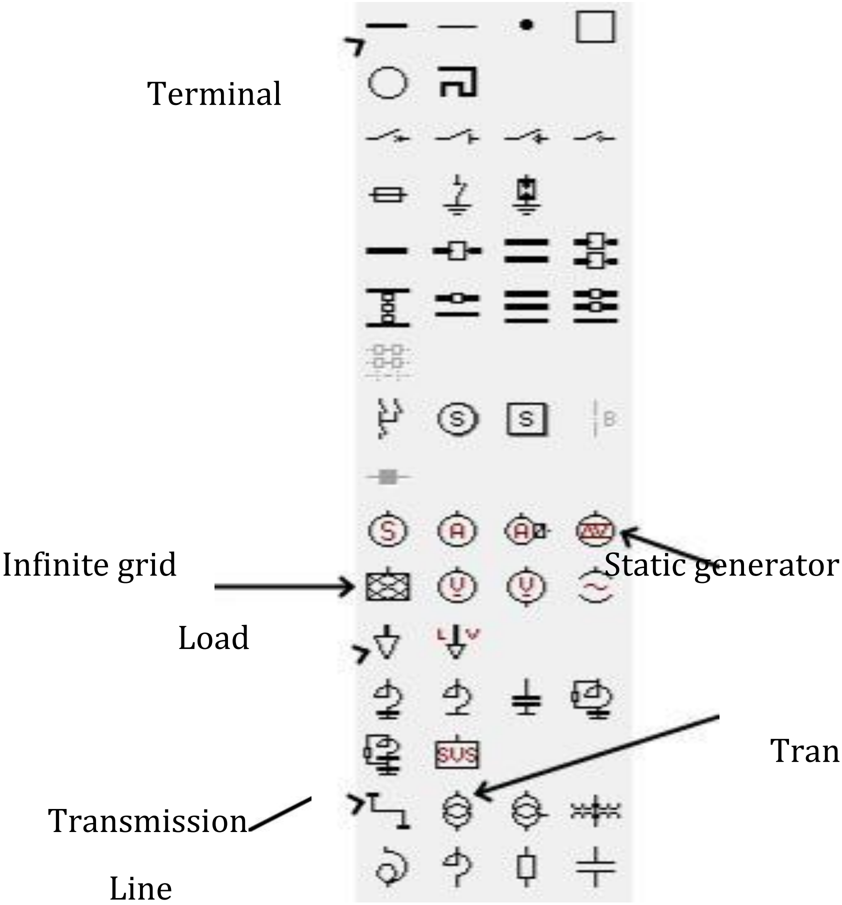


Figure 5.1: Grid elements as they are presented in DIgSILENT.

The above process refers to one set of calculations, e.g. a grid model has been implemented and all grid elements have values according to the desired values, then a possible execution of load flow would calculate the following quantities P, Q, |V|, δ in each node of the grid only once. In case, user wants to execute repetitive load flow calculations with different inputs, DPL script needs to be used.

DPL is a special feature provided by DIgSILENT and it allows the user to write a script similar to programming language C. Through this script user can perform modifications in every element of the grid and execute multiple calculations for multiple inputs.

A more detail of this software is given in Annexure 01.

CHAPTER 6

6. MODELING AND SIMULATION

6.1 Introduction

In conventional power systems electrical energy is produced by concentrated thermal power plants somewhere in the suburbs of a city and then it is transferred over medium or long distances to consumption areas where consumers are connected. In regular basis, the place a thermal plant is installed is nearby water or fuel installations. The reason of installing a thermal plant nearby water is in order to use it in the cycle of steam, lower the transportation cost of fuel and improve accessibility. Electricity grid has been dimensioned for one-direction load-flow and that is from thermal plant to consumer. Nowadays, situation has been changed and more and more DG / PV units are connected in the electricity grid, some of them in distribution level (higher installed power) and others in low voltage level (lower installed power). The main reason for increase of DG in the grid is the call for more and more "green" energy, energy with less CO_2 emissions and less dependency in fossil fuels. Installed power of DG units connected in the electricity grid was not significant and therefore the influence in grid parameters was low, but day after day and due to the increasing trend the influence increased considerably.

The objective of this chapter is to investigate through simulations the impact of DG connected in the electricity grid in LV level. As DG units are assumed PV plants connected in several nodes of the grid model. Through the following paragraphs the theoretical background for performing the simulations as well as a detailed description of the grid model and its elements is going to be presented.
Besides, DIgSILENT has set standards and trends in power system modeling, analysis and simulation for more than 25 years (DIgSILENT, 2013). The proven advantages of the PowerFactory software are its overall functional integration, its applicability to the modelling of generation-, transmission-, distribution- and industrial grids, and the analysis of these grids' interactions. This software provides a library of standard electrical components or models such as transformers, machines, and transmission lines. Therefore, the modelling and simulations are executed using DIgSILENT PowerFactory Version 14.1.3.

6.2 P.U. Base

The easiest way to analyze a balanced three-phase circuit is by a per-phase equivalent circuit with all Δ connections converted in their equivalent connections. The solution obtained can be extended to three phases knowing that the voltages and currents in other two phases would be the same except for the 120° phase shift. An advantage of per-unit representation is that circuits containing transformers can be easily analyzed. Real power systems are convenient to analyze using their per-phase (since the system is three-phase) per-unit (since there are many transformers) equivalent circuits. The per-phase base voltage, current, apparent power, and impedance are

$$I_{base} = \frac{S_{1\varphi,base}}{V_{1\varphi,base}}$$

$$Z_{base} = \frac{V_{LN,base}}{I_{\,base}} = \frac{\left(V_{LN,base}\right)^2}{S_{1\varphi,base}}$$

In the per-unit system, all the quantities are represented as a fraction of the base value,

$$Quantity\ in\ per-unit = \frac{Actutal\ value}{Base\ value\ of\ quantity}$$

In order to perform transformations from physical system to p.u. and vice versa, base values need to be known. In the present work, the base values used in all transformations are presented in **Table 6.1**

Table 6.1: Base units as they have been considered in calculations

Country	**Sbase**	**Ubase**	**Zbase**	**Lbase**
	MVA	**kV**	**Ohm**	**km**
Bangladesh	**33**	**11**	**2**	**1**

.

Where:

- S_{base} – Base apparent power.
- U_{base} – Base voltage.
- Z_{base} – Base impedance.
- L_{base} – Base length.

It is important to have all values in both physical and p.u. system in order to be able to set a proper base of transformation and achieve p.u. values, this way, systems with different physical values can obtain similar results in case structure remains the same.

For ins. there are various values for rated voltage in distribution grids around the world, in some countries the rated value of voltage could be in a range between 10kV and 60kV. This means that by setting base voltage equal to rated grid voltage the value in p.u. will be roughly 1 (this is the target of p.u. at first place) and therefore, results for two systems with different physical rated values but same structure will be in the same order and therefore it will be easier to draw conclusions. Besides, in DigSILENT POWER FACTORY software, all the values are considered in per unit basis.

6.3 Modeling of Photovoltaic Generator

Photovoltaic generator is based on semiconductor device and solid-state synchronous voltage source converter that is analogous to a synchronous machine except the rotating part. Voltage source converter in photovoltaic generator converts a DC input voltage into AC output voltage and supply active and reactive power to the system. It is a balance set of sinusoidal voltage at fundamental frequency with rapidly controllable amplitude and phase angle. A typical grid connected photovoltaic generator is shown in figure:

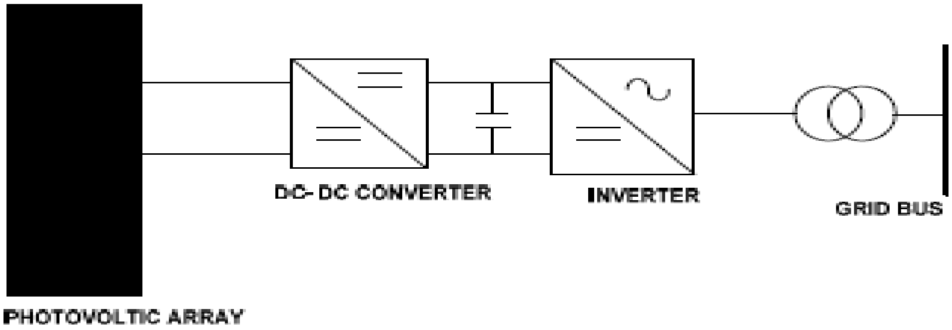


Figure 6.1: A typical grid-connected Photovoltaic Generator

6.4 Model Developments and Simulations

The development of an appropriate distribution network model is the focus of this section. This model will then be utilized through simulations in investigating some of the impacts of DG integration into the distribution network. The scope of the investigations is outlined in Section 6.4.1.

Standard component models have been chosen from DIgSILENT PowerFactory library in modeling the system for the investigations. The model being examined consists of an external grid (utility equivalent source) modeled as a Thevenin equivalent voltage source with a short circuit power.

6.4.1 Scope

The investigations are limited to the steady state phenomena such as short circuit contribution, voltage variation and protection coordination because issues such as transient stability are usually not critical factors at the distribution level [72], especially for radial feeders.
Distribution network being the emphasis for this work, these investigations are limited to low voltage distribution not exceeding the substation. However, it is known that DG can impact on the transmission network and vice versa.

6.4.2 Grid Model Description

As basic grid model of this work has been chosen a combination between a grid model which has been developed by DigSILENT and a real one existing in Bangladesh. This model is used as LV distribution network. For Bangladesh it is a real distribution feeder which supplies a small area named Housing Feeder in a small town, Comilla.

The rated voltage of the grid model is 11kV and it is supplied by one 33/11kV transformers interconnected in the “infinite grid”. Most connections are made with cables and there are used overhead lines too. The number of existing nodes is 15 and the whole grid is presented in **Figure 6.1**. As it can be seen, it is a single line diagram and is supplied by a 33/11kV transformer **TRA_33/11 KV** and an 11/0.4kV transformer **TRA_11/0.4 KV**, respectively.

In terms of loads, there are two loads. Here the loads of whole feeder are presented as two loads named **GL_1** and **GL_2** respectively to simplify the network but load characteristics are original. Here data of one year of Comilla S & D-2, Housing feeder is considered. The load characteristics curve of one hour interval of whole year is going to be varied to show the load variation.

Transmission lines connecting terminals between each other are 3 in total and they can be overhead lines or cables. In case of an overhead line there is more inductive behavior than cable and on the other hand, cables have more capacitive behavior compare to overhead lines. The number of PV plants integrated in the grid (as PV units) is one and it is varied with a variation of solar radiation data of one year which is presented in a time characteristics curve. Due to the structure of the grid, the influence of PV plants is going to be reflected. Besides, constant values of PV Generator also taken to show the impact of maximum PV generation.

There are 2 cases going to be investigated in this work through simulation software DIgSILENT to show the differences and they are presented below:

1. Electricity grid **with PV** plants in **radial structure**.
2. Electricity grid **without PV** plants in **radial structure**.

In connection to pre-mentioned cases, variation of 3 grid parameters is going to be investigated:

1. Grid voltage profile.
2. Transmission line losses.
3. Transformer loading.

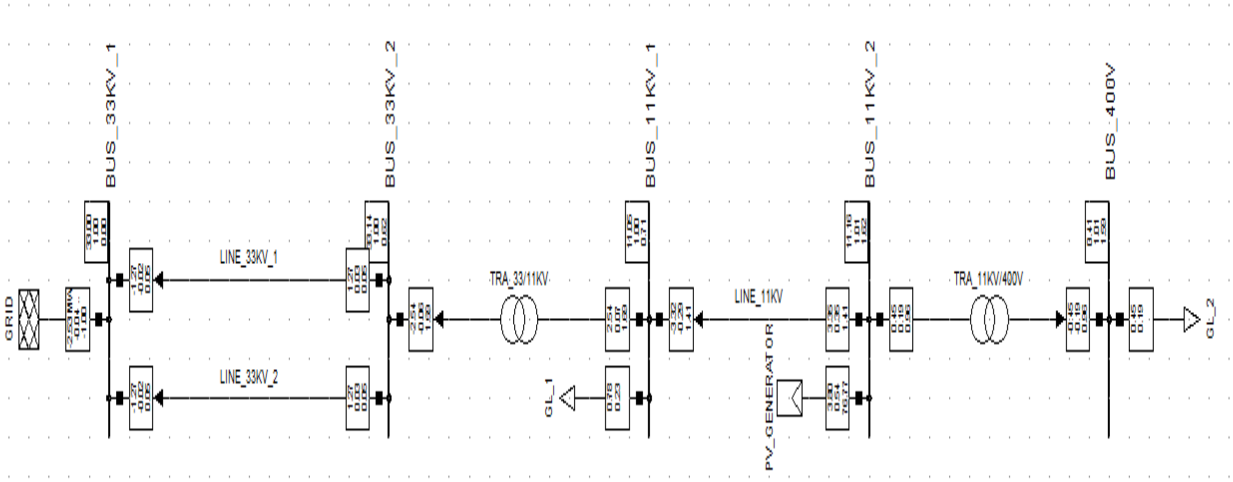


Figure 6.2: **A Model Single Line Diagram of a LV Distribution Network with PV Generator.**

The detail of infinite grid which is used in this software is shown in Table 6.2:

Table 6.2: **The detail of infinite grid**

Parameter	Unit	Value
Nominal system voltage	[kV]	33
Voltage value	[p.u.]	1.0
Voltage phase angle	[°]	0.0
R/X ratio	-	0.1

3 – PHASE TRANSFORMER:

The parameters regarding the transformer profile which has been used in the simulations are presented in **Table 6.3**.

Table 6.3: **The parameters of the transformer profile**

	Technology	3-Phases
	Rated power (MVA)	30
	Nominal frequency (Hz)	50
Rated voltage	HV-side (kV)	33
	LV-side (kV)	11
	Type	-
Positive sequence impedance	Short-circuit voltage uk1 (%)	5
	Copper losses (kW)	50
Zero sequence impedance, Short- circuit voltage	Absolute uk0 (%)	12
	Positive part ukr0 (%)	0.5

6.5 Power Flow Direction of A Model Diagram With PV

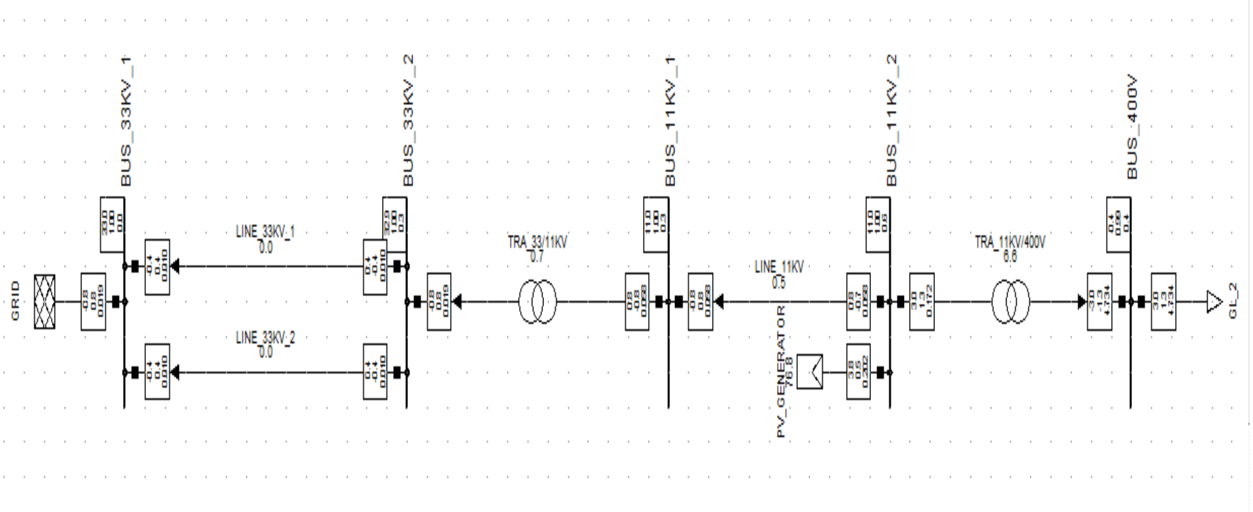


Figure 6.3: **Power Flow from PV Generator to Load and Grid.**

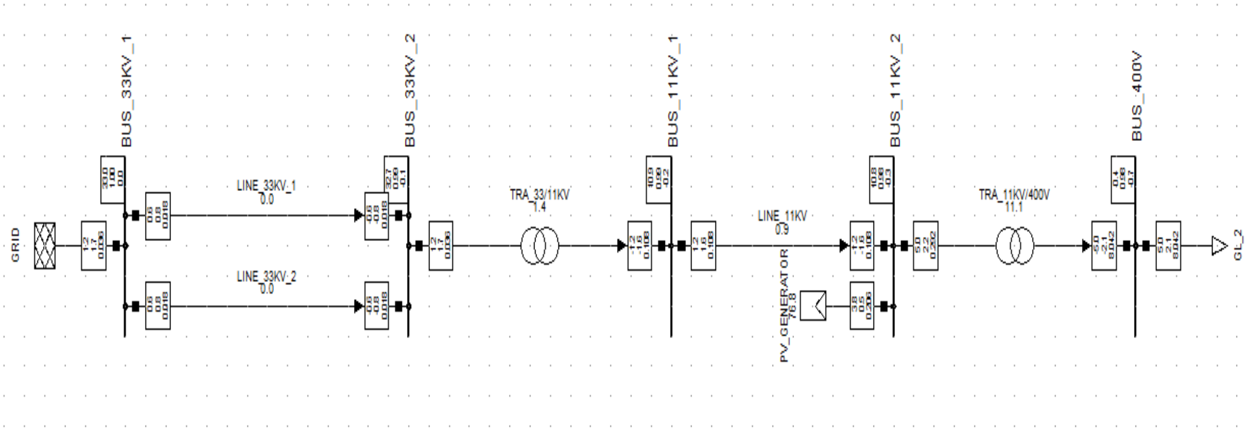
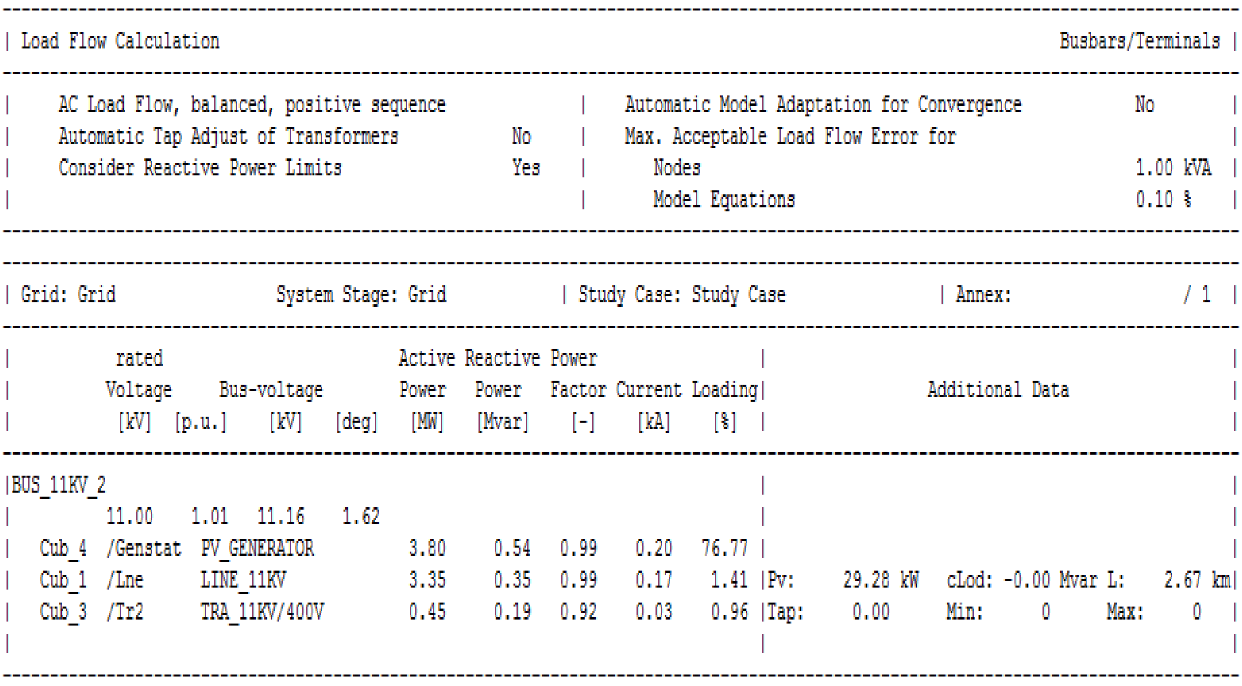


Figure 6-4: **Power Flow from Grid to Load.**

In a conventional radial grid structure, Power flows from the grid to the loads. From Figure 6-2; when PV Generator is connected, it is showed by the arrow direction that, power flows from the PV Generator to the load and to the grid when PV Generator generates more than the Load. After meeting the load, an amount of surplus electricity generation goes to the grid which is the main concept of PV to Grid Integration. In this case, the electricity flow reverses direction and the voltage rises as it goes to the end. In Figure 6-3, when PV Generator generates less than the load demand, the rest of the electricity is supplied from the grid to meet up the load demand is shown through the arrow direction.

6.6 Power or Load Flow Analysis

Another theoretical knowledge required for simulation of a power system during steady state is load (or power) flow analysis. DIgSILENT which is used in simulations takes into consideration the theory of the present paragraph in order to calculate load flow. In this paragraph the most important is the iterative mathematical process which is used in order to calculate the actual power flow in the grid.



```
------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                 Busbars/Terminals |
------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence          |   Automatic Model Adaptation for Convergence         No      |
|    Automatic Tap Adjust of Transformers         No     |   Max. Acceptable Load Flow Error for                       |
|    Consider Reactive Power Limits               Yes    |      Nodes                                         1.00 kVA  |
|                                                       |      Model Equations                               0.10 %    |
------------------------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------------------
| Grid: Grid                 System Stage: Grid            | Study Case: Study Case              | Annex:              / 1  |
------------------------------------------------------------------------------------------------------------
|          rated                        Active Reactive Power                 |                                        |
|         Voltage     Bus-voltage        Power    Power   Factor Current Loading|           Additional Data              |
|          [kV]  [p.u.]    [kV]    [deg]   [MW]   [Mvar]    [-]    [kA]    [%]  |                                        |
------------------------------------------------------------------------------------------------------------
|BUS_11KV_2                                                                    |                                        |
|         11.00    1.01   11.16    1.62                                         |                                        |
|   Cub_4  /Genstat  PV_GENERATOR        3.80    0.54   0.99    0.20   76.77 |                                        |
|   Cub_1  /Lne      LINE_11KV           3.35    0.35   0.99    0.17    1.41 |Pv:     29.28 kW   cLod: -0.00 Mvar L:    2.67 km|
|   Cub_3  /Tr2      TRA_11KV/400V       0.45    0.19   0.92    0.03    0.96 |Tap:     0.00      Min:      0      Max:    0  |
|                                                                              |                                        |
------------------------------------------------------------------------------------------------------------
```

Figure 6.5: **Power or Load Flow Analysis**

6.7 Steady State Analysis of A Typical LV Distribution Network

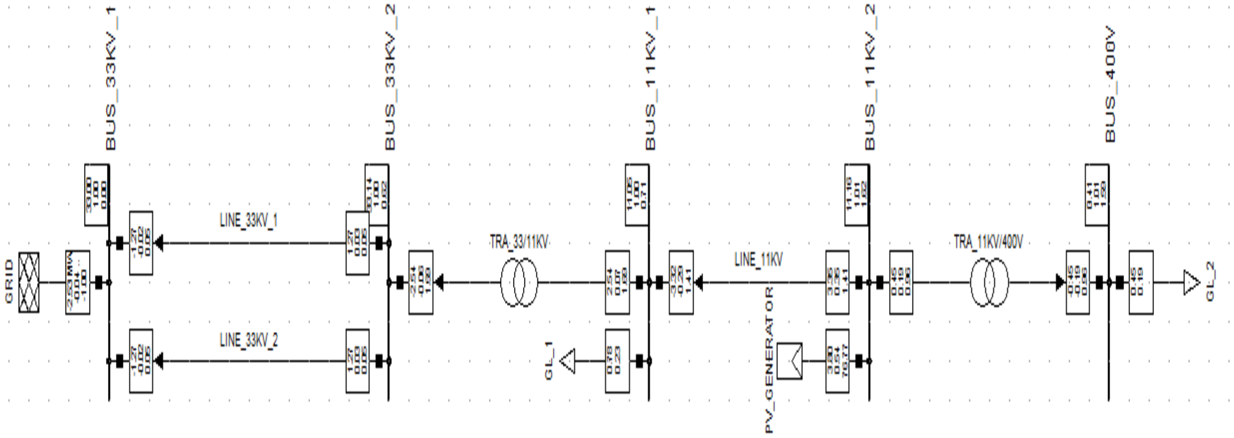


Figure 6.6: **A LV Distribution Network with Fixed Load**

6.7.1 Voltage Stability Analysis With And Without PV Generator

From Figure 6-7, the voltage profile of a 11 KV bus without PV Generator can be observed. The graph shows various up and downs and the magnitude of the curve varies between 0.99 p.u. (the upper limit) to 0.91 p.u.(the lower limit). When I added PV Generation to the same bus, the bus voltage starts from 0.99 p.u., reaches above 1.09 p.u. and then after a while when load is increased too much reaches to 0.91 p.u.. With PV, the curve is quite smoother than without PV. The voltage level shows much difference in case of with and without PV. Grid- connected photovoltaic generation system includes PV array, Inverter and its controller and conventional power equipment. PV array converts light energy from the sun into DC electrical energy and PV inverter, converting direct currents to alternating current, is interfaced with power system through combiner boxes and step-up Transformer.

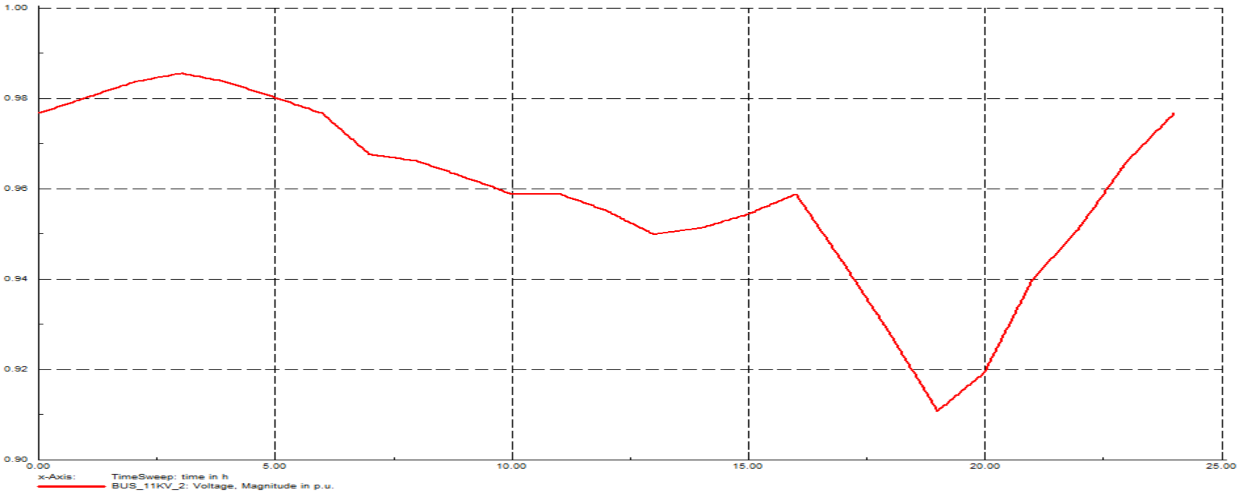


Figure 6.7: **Voltage Curve against 11 kv bus without PV**

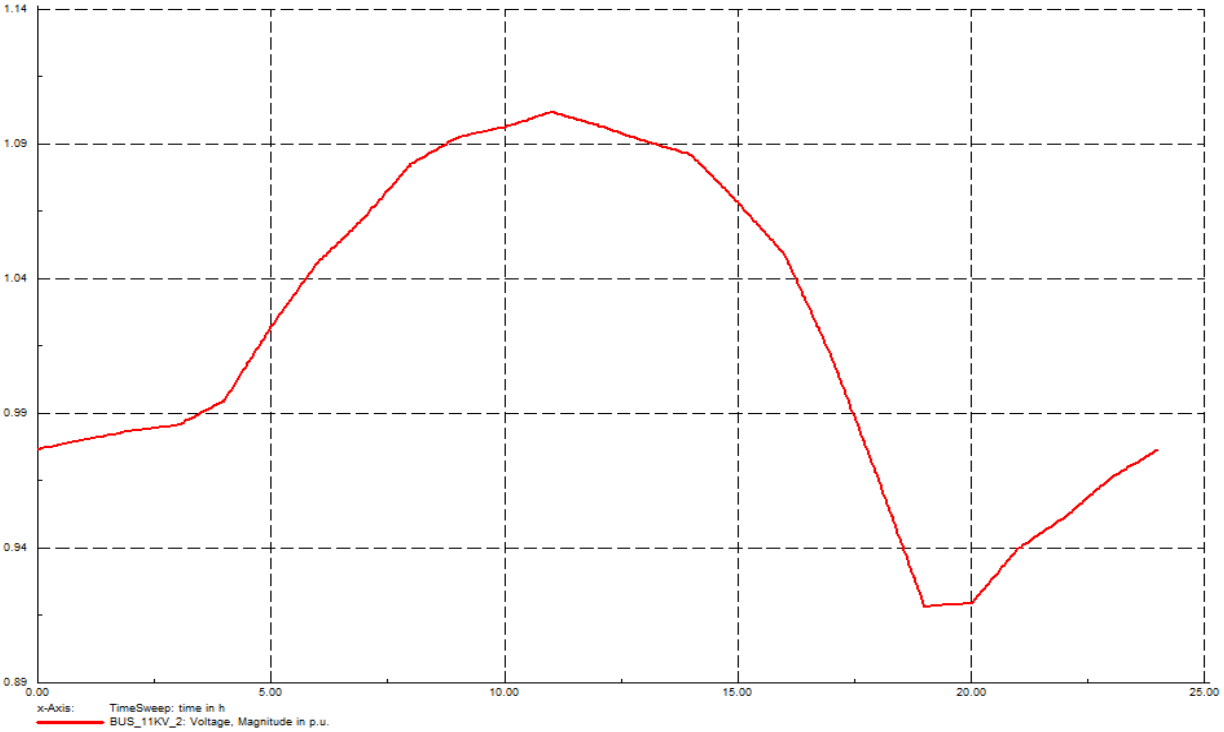


Figure 6.8: **Voltage Curve against 11 kv bus with PV**

Through the inverter harmonics or reactive component enters the grid system which has adverse effect on the voltage stability. When PV output increases, grid voltage also increases simultaneously. Due to the variation of solar irradiance, PV output power varies. In case of high ramp rates of solar irradiation, bus voltage goes high beyond its tolerable limit as reactive components associated with the positive or negative peaks of solar quality. But when it crosses the tolerable limit, bus or feeder is disconnected from the grid frequently. The tolerable limit of bus voltage is 0.95 p.u. to 1.05 p.u. From Figure 6-8, we can see that, with increasing solar radiation, bus voltages crosses the limit of 1.05 p.u. and then collapses. But within the voltage limit, it gives better power quality. Abrupt changes are not seen from the curve.

6.7.2 Frequency Response Analysis with PV Generator

The integration of PV into a LV distribution network does not affect the system frequency abruptly. As the grid always supports the LV distribution network, the changes in system frequency with increasing or decreasing amount of PV Generation cannot be shown. The integration of PV into a transmission system affects the system frequency very much. As i could not add harmonics into the system, the system frequency remains between the frequency limit of 49.9 to 50 Hz.

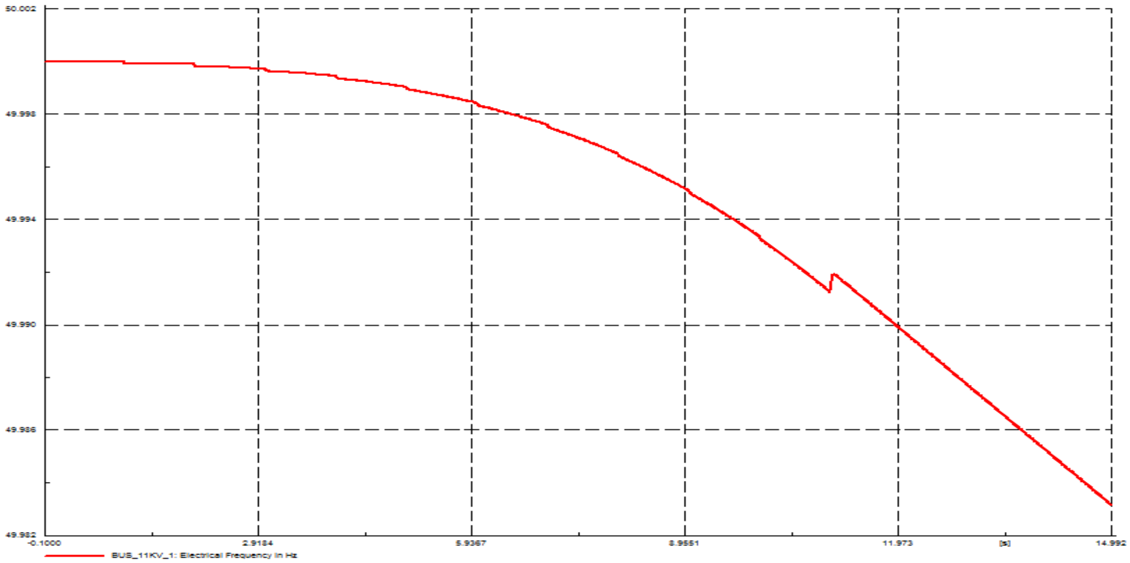


Figure 6.9: **Frequency Response with PV**

6.7.3 Critical Point Of Static Voltage Instability

Bus loadability is another crucial factor that can affects the entire system. The reactive power support that the bus receives from the system, can limit loadability of that bus and hence the entire system. The maximum loadability of PV generation also affects the entire system. Once the bus voltage reaches to its maximum loadability limit due to PV generation, the bus voltage collapses and disconnected from the entire system.

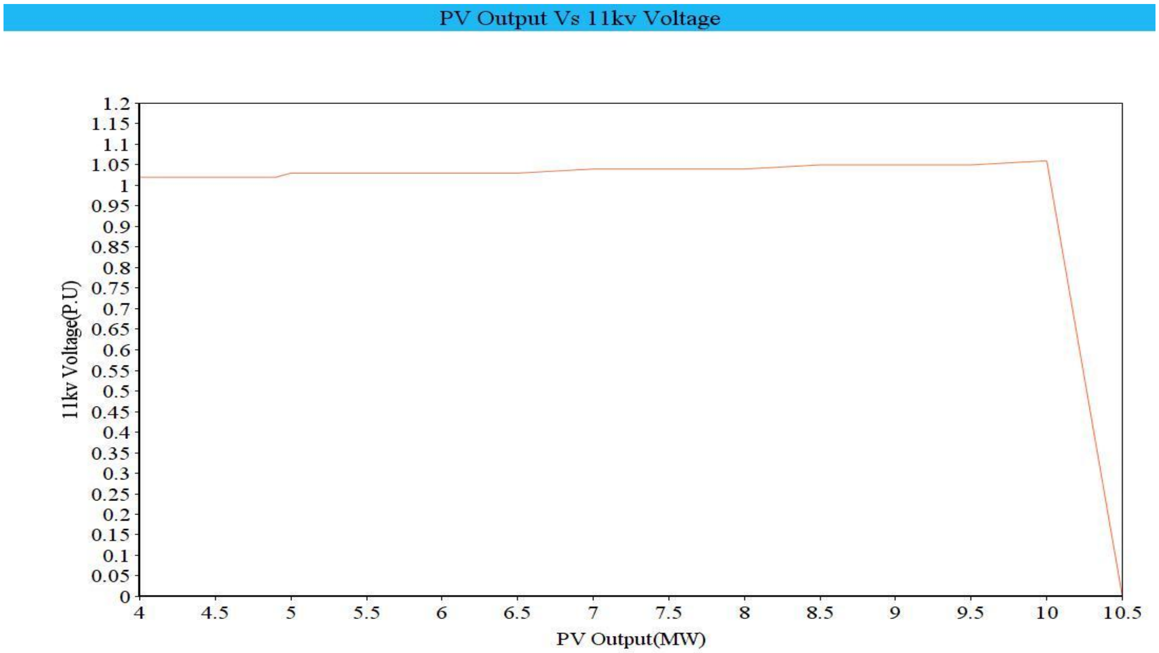


Figure 6.10: **PV output VS 11 KV Bus Voltage**

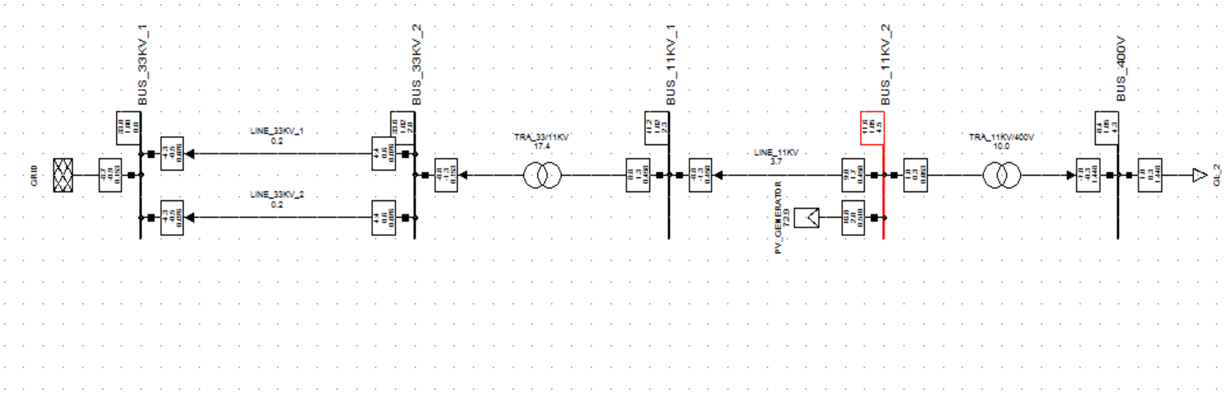


Figure 6.11: **Bus disconnected due to overloading**

From figure-10 and figure -11, it is shown that, when bus voltage reaches to 1.06 p.u. due to more than 10 MW PV Solar generation, the bus is disconnected from the distribution network.

6.8 CASE STUDY 1: Voltage Stability Analysis of A Feeder Of Bangladesh Using Time Characteristics Curve Of One Year

To observe the impact of PV generation on voltage stability of a real power system, I have taken Comilla S & D 2: 11 KV Housing Feeder. Here I have considered the one year load data of that feeder and one year solar radiation data of the area. Then I have injected the whole year solar radiation data to the PV Generator and also varied the load pattern of whole year.

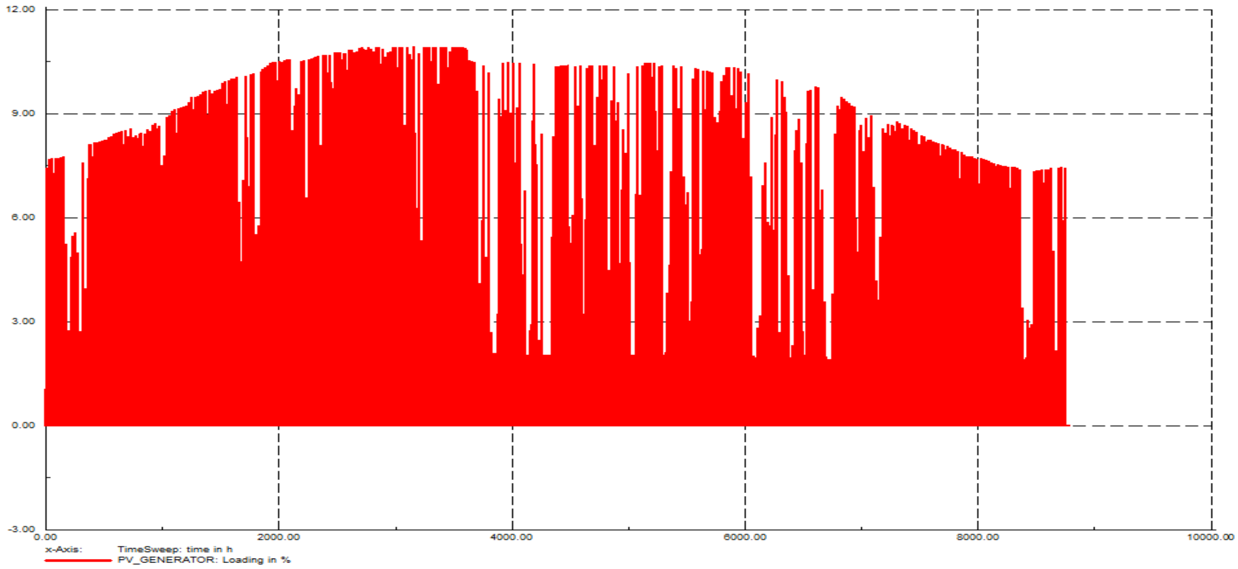


Figure 6.12: **Load data of one year of Housing Feeder**

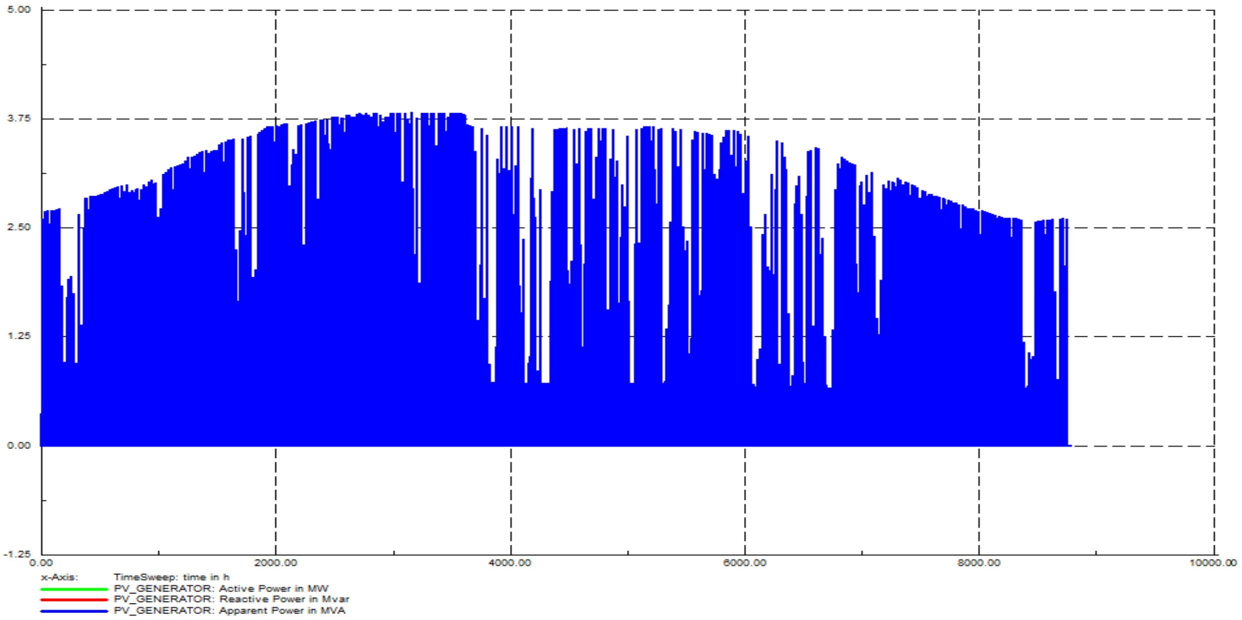


Figure 6.13: **Solar radiation data of one year**

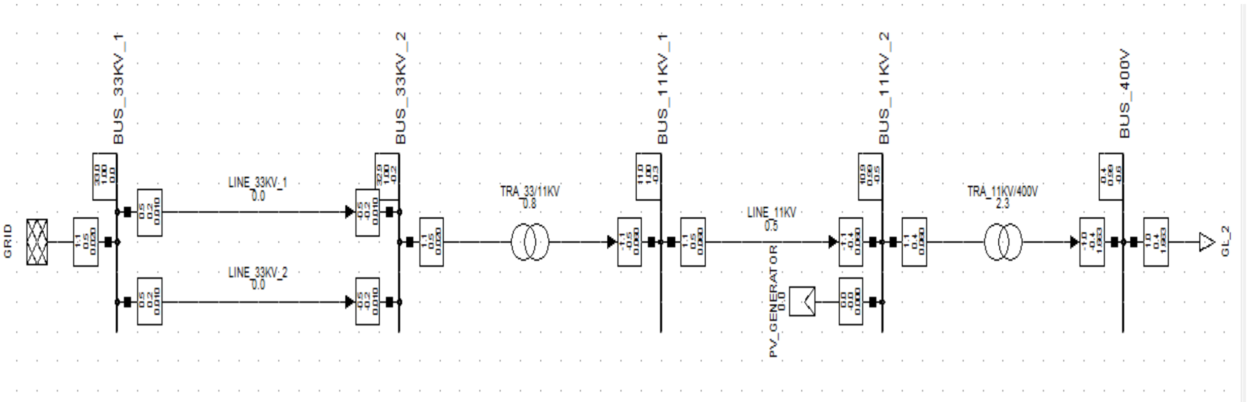


Figure 6.14: **11 KV Feeder**

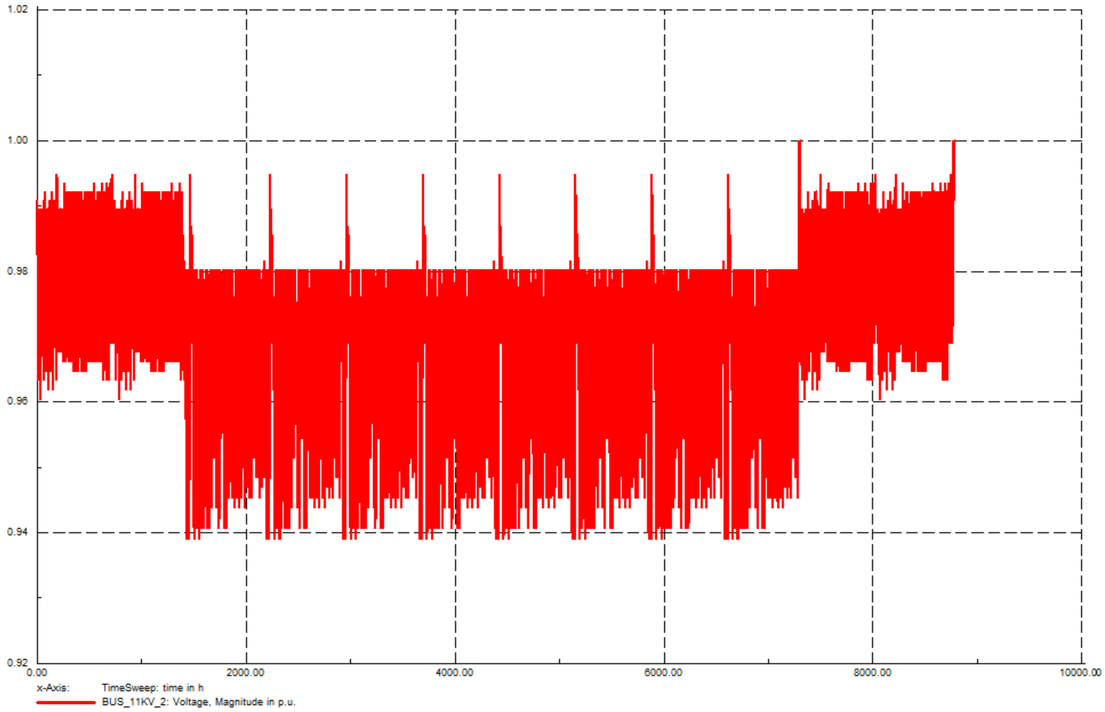


Figure 6.15: **11 kv bus voltage without PV**

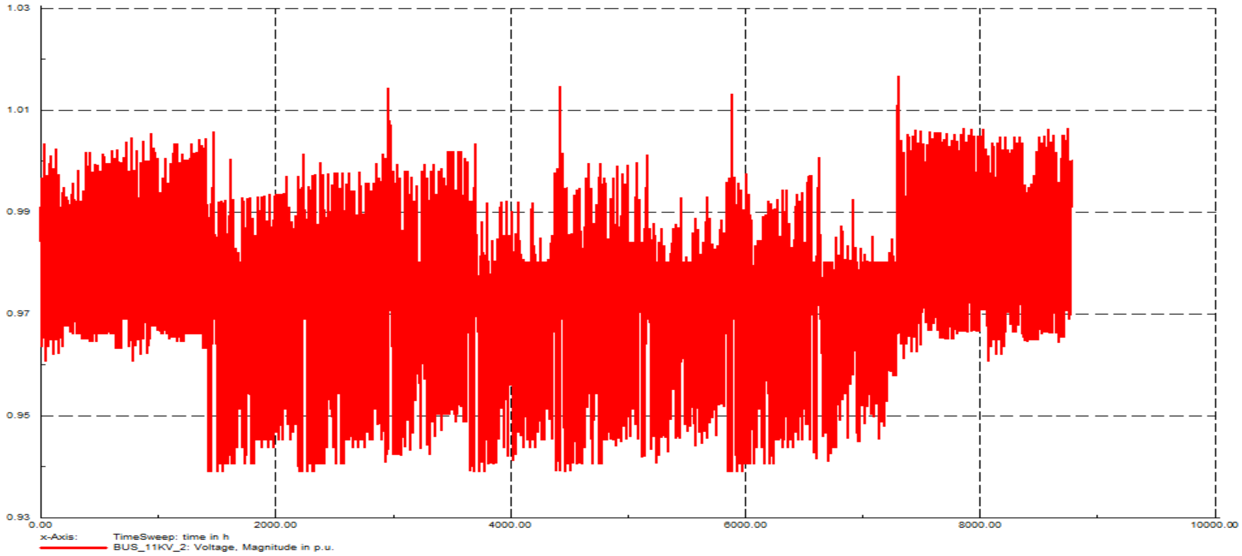


Figure 6.16: **11 kv bus voltage with PV**

6.8.1 VOLTAGE STABILITY ANALYSIS

Figure 6-16 and Figure 6-17 are showing the 11 KV bus voltages with and without PV. From these figure it is clear that with PV, voltage magnitude is higher than voltage magnitude without PV when sudden ramp of solar radiation is coming. Otherwise, the voltage pattern is much smoother in case of PV generation than without generation. This is the abrupt behavior of PV solar generation.

6.8.2 LINE LOSSES ANALYSIS

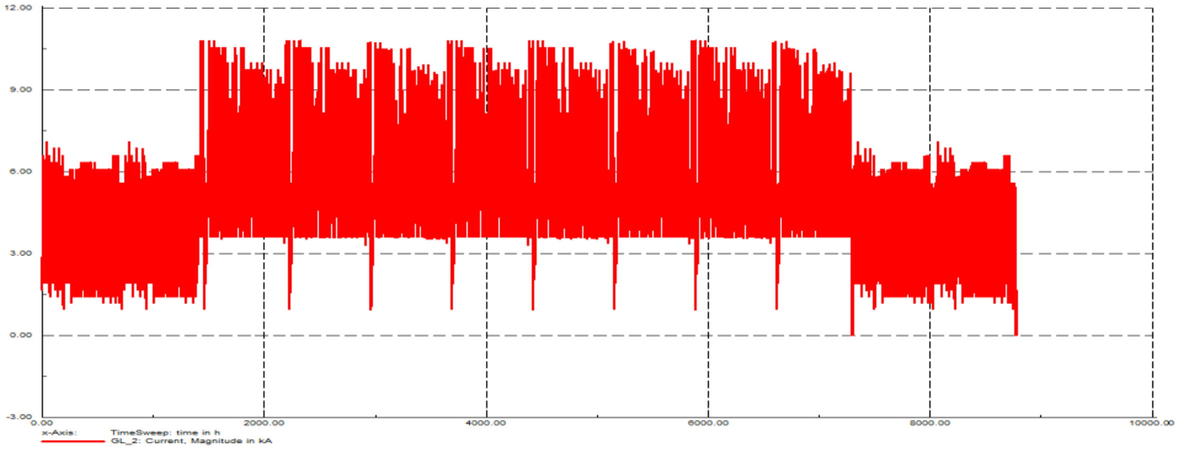


Figure 6.17: **Current against load with PV**

As bus voltage increases with increasing PV generation, current also increases. We know that Losses = I^2R, so losses of distribution Lines also increases.

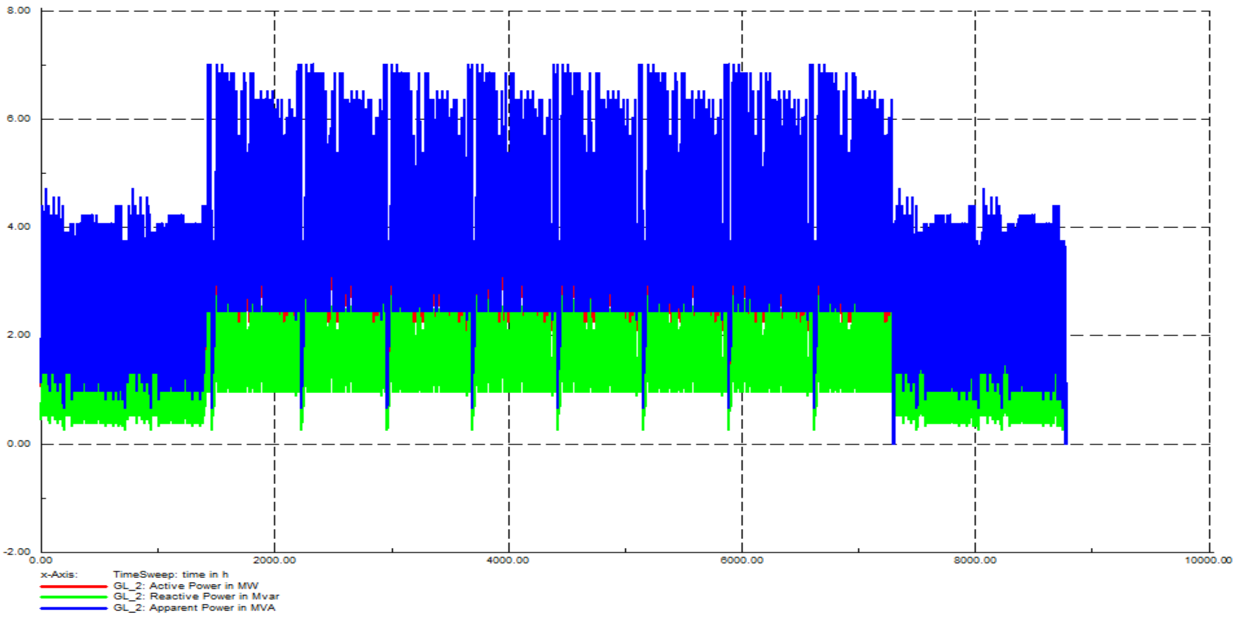


Figure 6.18: **Power against load with PV**

6.8.3 Transformer Loading Analysis

From figure 6-18 and figure 6-19, I have got the pattern of loading of transformer with PV generation and without PV generation. PV generation decreases the overloading problem of transformer. If we add PV generator with overloading transformer, some percent of loading of transformer has decreased with PV generation. Due to reactive component of PV generation, it helps to improve the voltage level as well as decreases the overloading effect of transformer. But it is happened only for some percentage increase of PV generation. If we add too much PV generation, then overloading effect increases at a high rate.

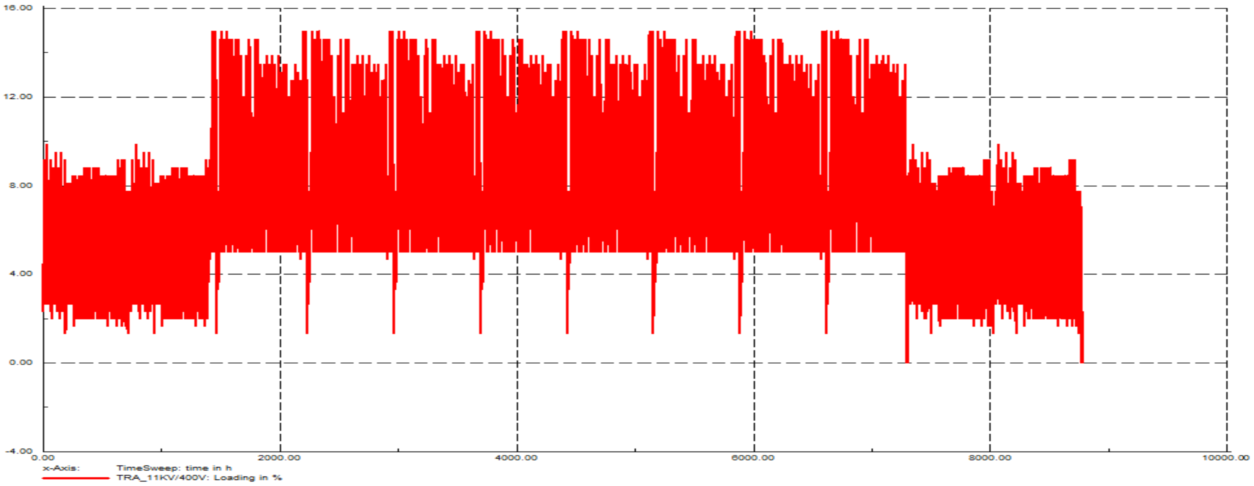


Figure 6.19: **Transformer loading without PV**

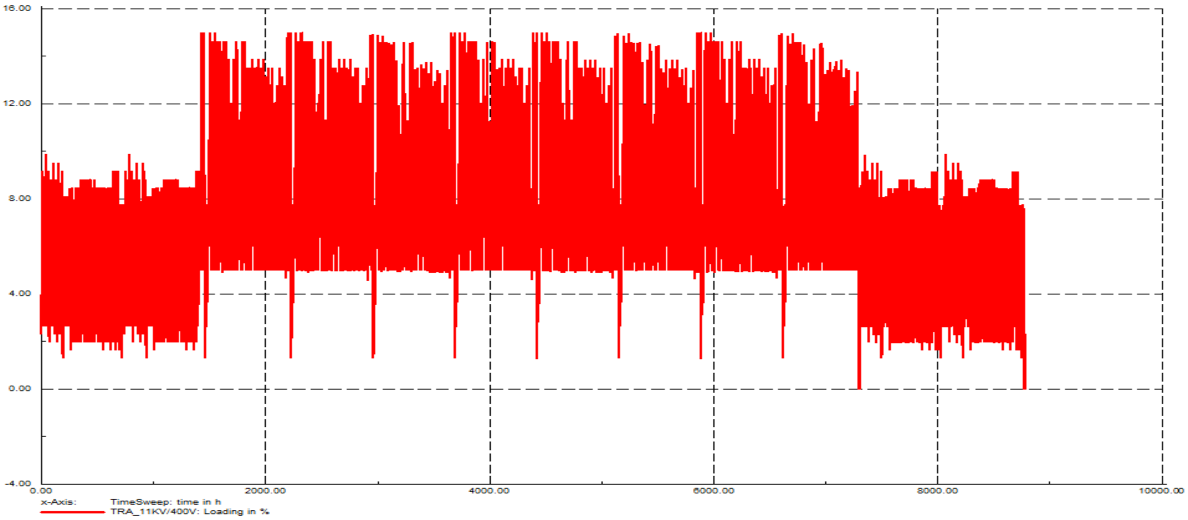


Figure 6.20: **Transformer loading with PV**

6.9 CASE STUDY 2: Analysis of An Urban Feeder Running At Voltage Stability Limit

In 33/11 kV Dhanmondi grid, one 11 kV bus voltages are found as follows:

Table 6.4: **In 33/11 kV Dhanmondi grid, one 11 kV bus voltages**

Time	Voltage (KV)
1	10.7
2	10.7
3	10.8
4	10.8
5	10.7
6	10.7
7	10.7
8	10.8
9	10.7
10	10.7
11	10.6
12	10.6
13	10.9
14	10.5
15	10.8
16	10.9
17	10.8
18	10.8
19	11
20	11.2
21	11
22	11
23	11.2
24	11.2

All 7 buses of the substation had the identical voltage condition that is running at voltage stability limit. From these data, it is clear that bus voltages are running at the critical voltage limit as the critical limit is between 10.45 KV to 11.5 KV. If we add solar Photovoltaic generation to this grid, only 4 to 5 MW added PV generation will collapse the buses frequently. So, Overloaded or overvoltage buses are not good choice to inject solar Photovoltaic generation. Otherwise consumer of those feeders will have to tolerate adverse effect.

6.10 Evaluating Penetration Factor for case study 1:

Penetration Factor: It means how much energy of Solar PV generation of the total generation can be injected to the grid.

For one of the feeder of Comilla S & D-2, I have calculated the maximum PV Penetration factor using the solar radiation data of one year and also using the load data of that feeder of one year through DigSILENT Power Factory Software.

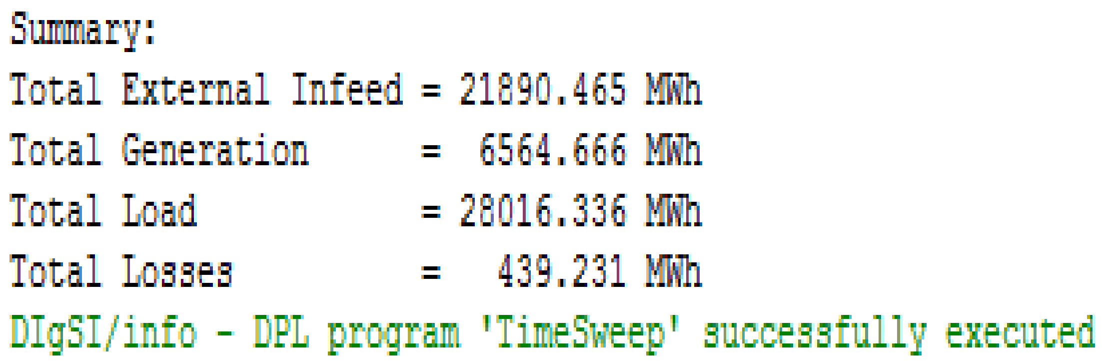
- For PV penetration (%) generation based = Total PV generation (MWh)/ Total

  Generation (MWh)

  = 6564.666* 100/28016.336

  = 23.43%

From DigSILENT Power Factory, I have found the following data:



```
Summary:
Total External Infeed = 21890.465 MWh
Total Generation      =  6564.666 MWh
Total Load            = 28016.336 MWh
Total Losses          =   439.231 MWh
DIgSI/info - DPL program 'TimeSweep' successfully executed
```

CHAPTER 7

7. CONCLUSION AND RECOMMENDATIONS

7.1 Findings

Based on the topics have been discussed in the chapters of this thesis, the following findings have been found:

- It has been shown that PV plants (as DG units) have significant influence in grid parameters such as voltage stability, transmission line losses, system frequency and transformer loading.

- In case of PV plants connected in the grid during daylight, the bus voltage is higher compared to the case without PVs when bus voltage remains in the tolerable limit which is 0.95 p.u. to 1.05 p.u. This leads to an overall better voltage profile in favor of consumers.

- With increasing solar radiation, when bus voltages crosses the limit of 1.05 p.u., the bus voltage collapses or disconnected from the power system . It is the most crucial effect of PV Penetration. It has severe effect to the electrical equipment of the consumer as the equipment cannot tolerate sharp voltage drop.

- Due to the dependence of power flowing through transmission lines on the power produced by PV plants, a variation has been recorded in transmission line power flow and it is depended on solar irradiation, as power production from PV plants is linearly related to solar irradiation.

- By varying frequency with grid voltage, could not find frequency response instability due to grid instability. As there is always present grid in the LV distribution network and this PV generator does not produce enough harmonic content, the frequency response curve remain within the grid stability limit. Besides Frequency response of grid Instability can be found in the Transmission side as frequency has greater impact on transmission side.

- As bus voltage increases with increasing PV generation, current also increases. So line losses of distribution lines also increase. It reduces longevity of distribution lines.

- PV generator has a vital effect on overloading transformer as some percent of loading of transformer has decreased with integrated PV generation. Due to reactive component of PV generation, it helps to improve the voltage level as well as decreases the overloading effect of transformer. But if we integrate too much PV generation, then overloading effect increases at a high rate.

- The penetration factor shows that, PV generation should be 23%- 25% of the total demand for a rural feeder. Otherwise the consumers as well as distribution networks have to tolerate detrimental effect of PV generation.

7.2 Recommendation

The study suggest, before integrating Solar PV to grid, grid voltage stability, line losses, maximum penetration factor should be analyzed or counted. Otherwise distribution network will collapse frequently, under voltage or overvoltage will destroy the electrical equipment's and grid can also collapse.

The study also suggest that, in the urban area where already over voltage is existed, it will not be wise to integrate a good percentage of solar PV generation to that network. It will be the cause of grid instability. On the other hand, it will be good for our country, Bangladesh if we take initiative to plan to integrate a considerable percentage of solar PV generation to the rural areas.

As PV plants produce "green" energy, it is becoming a more concerning issue. But on the other hand, due to the spinning reserve which needs to be increased the energy produced by PVs is not 100% "green".

7.3 Future Scope of Work

Integration of PV generation is a vast issue and many works can be done with it. As PV plants produce "green" energy, it is becoming a more concerning issue. I would like to do work with the transmission side of the power system, protective devices of the transmission or distribution side. As I could not show the frequency instability, it will also be a future concern for me.

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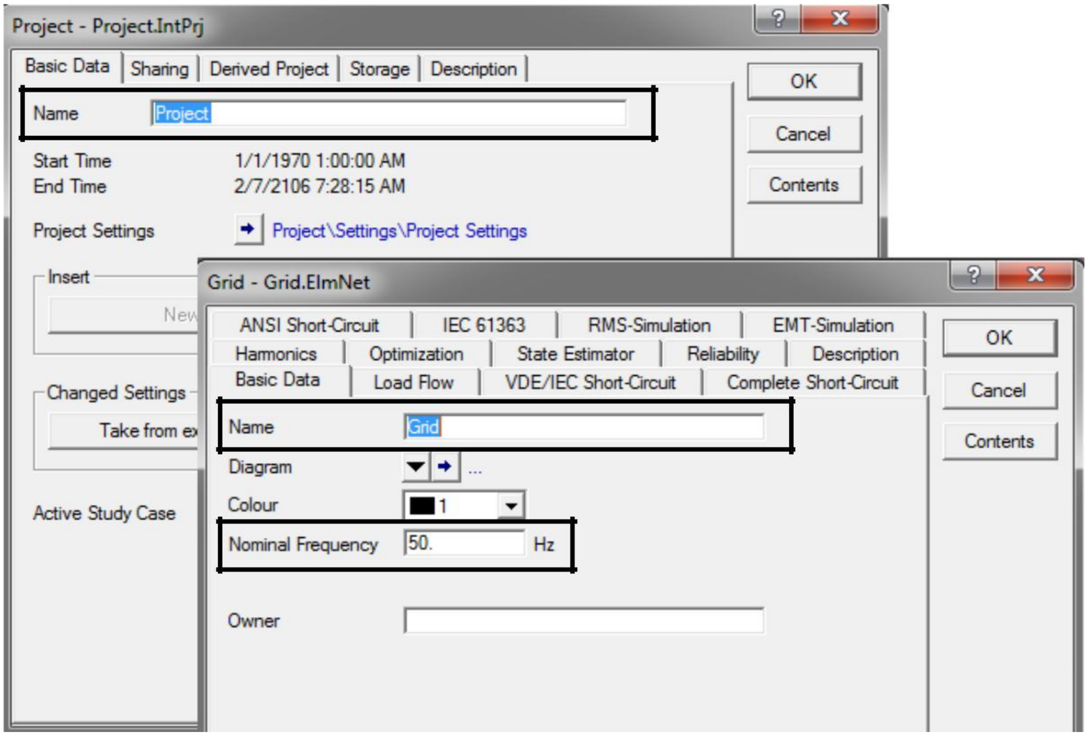
Annexure 01: Steps of analysis with DIgSILENT PowerFactory

First thing before establishing a grid model is the preparation of the project. There are three basic fields need to be filled in this process, first is the name of the project, then it is the name of the grid model which is going to be used in the project and last thing is the definition of the nominal frequency of the grid. The way those fields are presented in the software is illustrated in **Figure 1**.



Name: Project
Start Time: 1/1/1970 1:00:00 AM
End Time: 2/7/2106 7:28:15 AM
Project Settings: Project\Settings\Project Settings

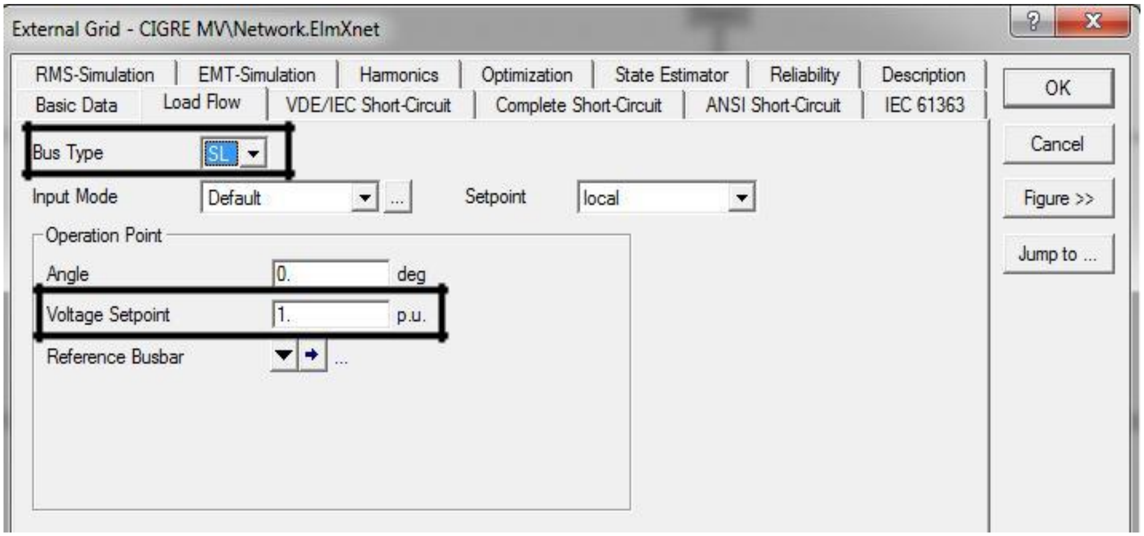
Name: Grid
Colour: 1
Nominal Frequency: 50. Hz

Figure 1: Initial steps for project set-up.

First, from all grid elements, it has been chosen to present the "External grid", this choice was not arbitrary, the External grid represents the "infinite grid" in calculations or it can be said that it is the connection point between the rest of the electricity grid and the simulated grid model.

In terms of settings, there are three to be done. First a name needs to be given (this does not influence the load flow) then, type of bus needs to be chosen and last is voltage set-point.

Due to the fact that it represents the "infinite grid", and there is no other generator declared as slack generator, this External grid element is going to be declared as slack generator. Considering voltage set-point of the slack bus, it needs to be 1.0 p.u., in **Figure 2** settings concerning load flow are presented.



Bus Type: SL

Input Mode: Default

Setpoint: local

Operation Point

Angle: 0. deg

Voltage Setpoint: 1. p.u.

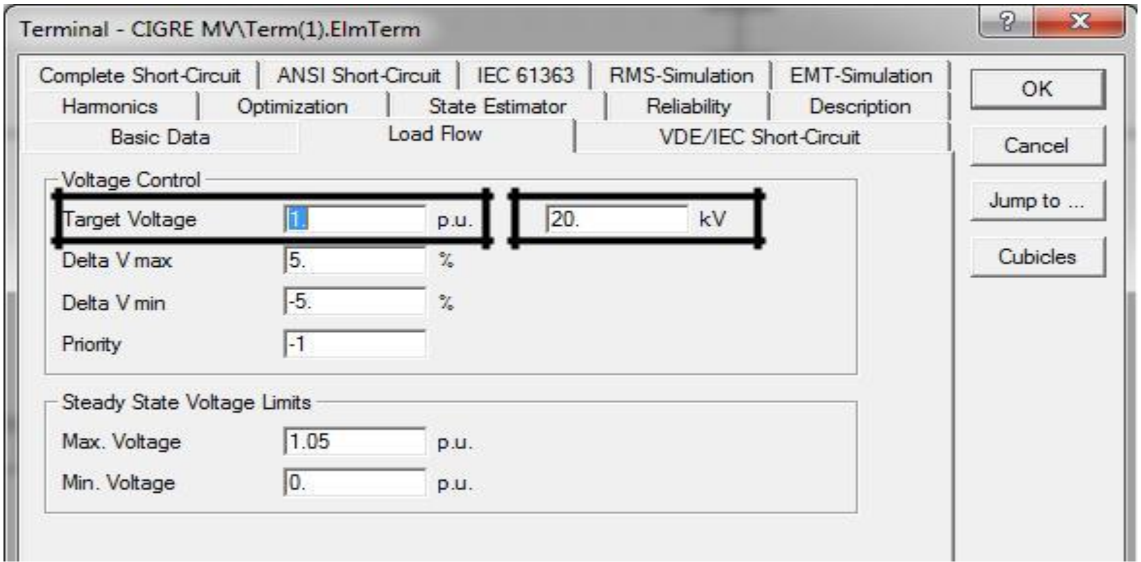
Reference Busbar

Figure 2: Load flow settings for “External grid”.

Another important grid element in order to implement a grid model is the “Terminal”. Terminal elements are used several times in grids in order to connect e.g. one transmission line with another or a transformer with a transmission line and loads, etch. In general is a connection point between various elements in the electricity grid.

In order to achieve a connection between the connection point and e.g. a load, a breaker needs to be used, the purpose of using a breaker is to give the opportunity to connect or disconnect an element by connecting or disconnecting a breaker.

A Terminal element has three settings. First is the name of the Terminal, then is the Target voltage in p.u. and then is the Target voltage in kV. Settings for Terminal element are presented in **Figure 3**.



Voltage Control

Target Voltage: 1. p.u. 20. kV

Delta V max: 5. %

Delta V min: -5. %

Priority: -1

Steady State Voltage Limits

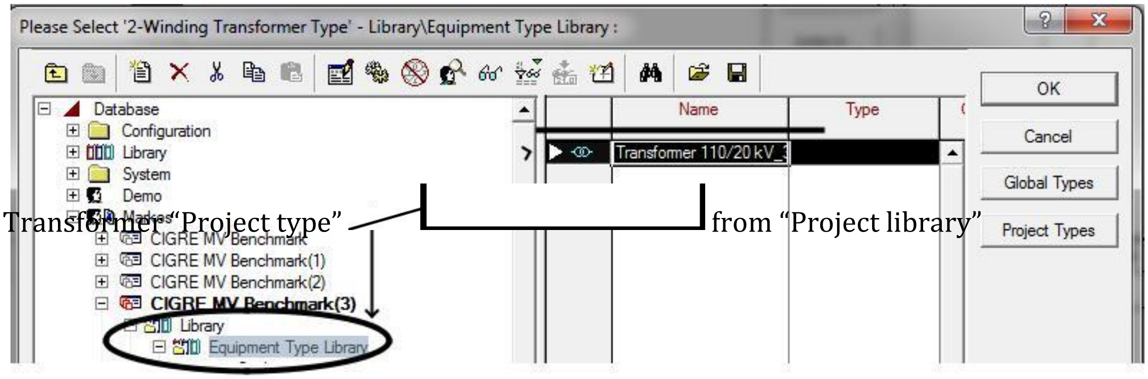
Max. Voltage: 1.05 p.u.

Min. Voltage: 0. p.u.

Figure 3: Load flow settings for "Terminal".

DIgSILENT provides the ability to create grid elements according to current project which can be used multiple times in the grid model. One of these grid elements is the transformer, due to 13 settings one transformer profile demands, it is not convenient to built another transformer profile each time one needs to be used. Therefore, in case the same transformer can be used multiple times, only one profile is built and can be used several times (**Figure 4**).

The mandatory fields need to be filled for a transformer profile, are presented in **Figure 4**.

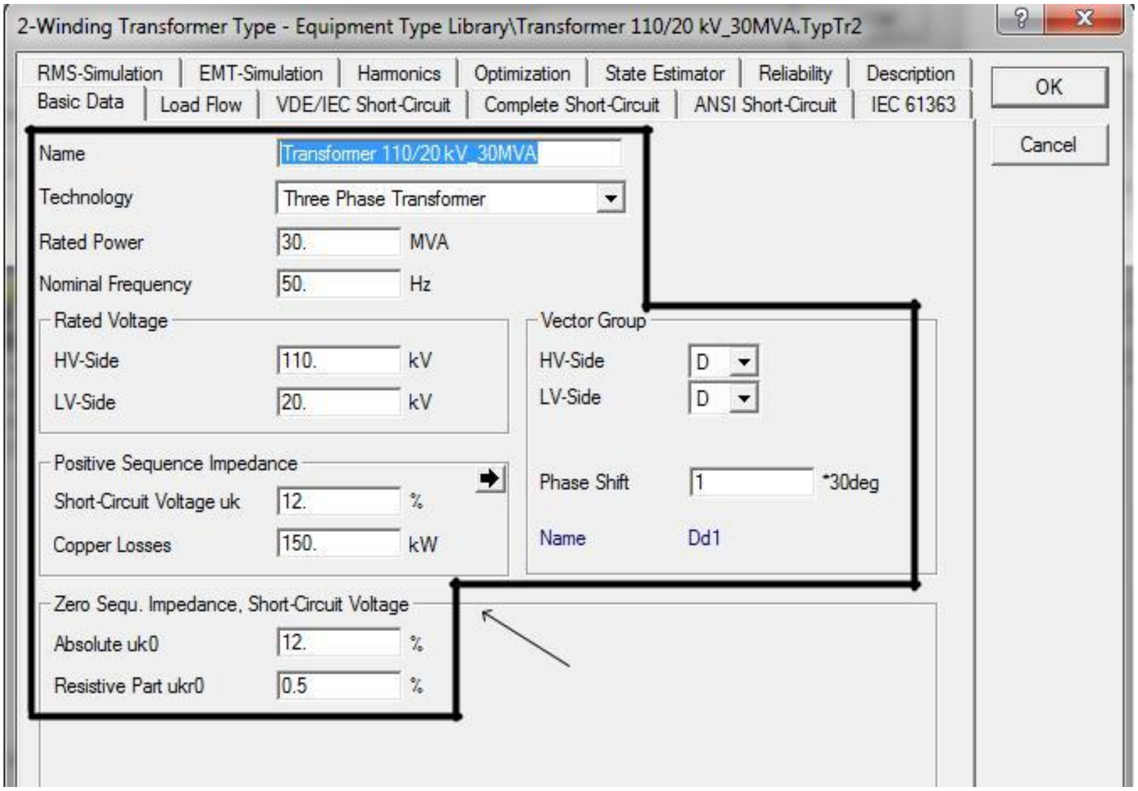

Please Select '2-Winding Transformer Type' - Library\Equipment Type Library :

- Database
  - Configuration
  - Library
  - System
  - Demo
  - Makes
    - CIGRE MV Benchmark
    - CIGRE MV Benchmark(1)
    - CIGRE MV Benchmark(2)
    - **CIGRE MV Benchmark(3)**
      - Library
        - Equipment Type Library

Name	Type
Transformer 110/20 kV_3	

Transformer "Project type"

from "Project library"


2-Winding Transformer Type - Equipment Type Library\Transformer 110/20 kV_30MVA.TypTr2

Name: Transformer 110/20 kV_30MVA

Technology: Three Phase Transformer

Rated Power: 30. MVA

Nominal Frequency: 50. Hz

Rated Voltage

HV-Side: 110. kV

LV-Side: 20. kV

Vector Group

HV-Side: D

LV-Side: D

Phase Shift: 1 *30deg

Name: Dd1

Positive Sequence Impedance

Short-Circuit Voltage uk: 12. %

Copper Losses: 150. kW

Zero Sequ. Impedance, Short-Circuit Voltage

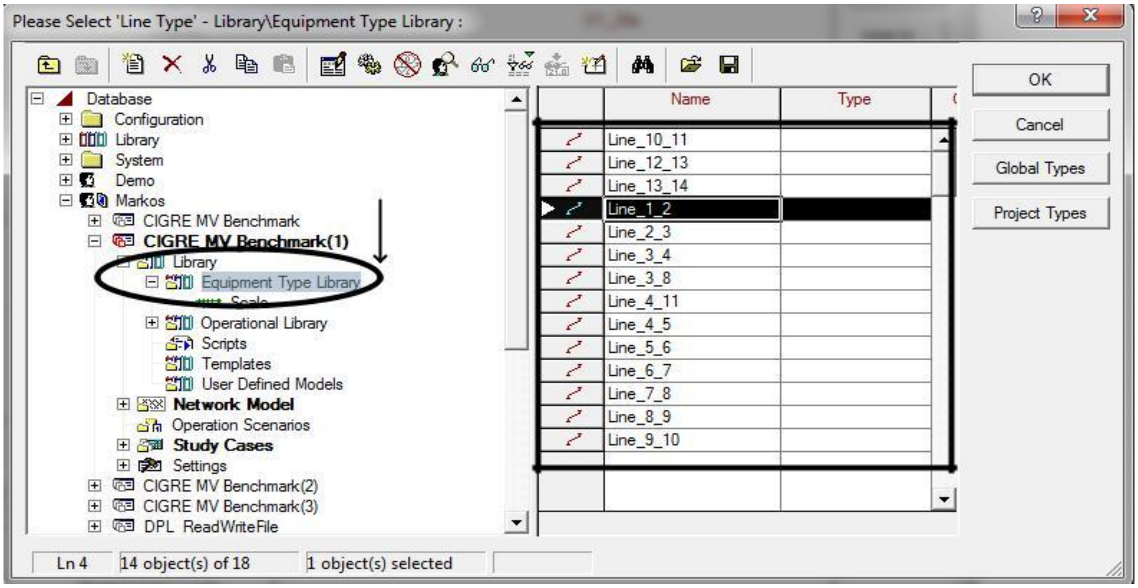
Absolute uk0: 12. %

Resistive Part ukr0: 0.5 %

Figure 4: Choice of "Project type" transformer, settings for "Project type" transformer

"Transmission line" element is used in order to establish connection between nodes in the same grid model. Similar to Transformer element, it is possible to create Transmission line profiles according to project and use them multiple times in the same grid model. For instance, there are 14 Transmission line profiles depicted in **Figure 5-a**.

As settings for a Transmission line profile are inputs like e.g. overhead line or cable, rated voltage and current, resistance and reactance, etch. The fields as well as some indicative input values are presented in **Figure 5-b**.



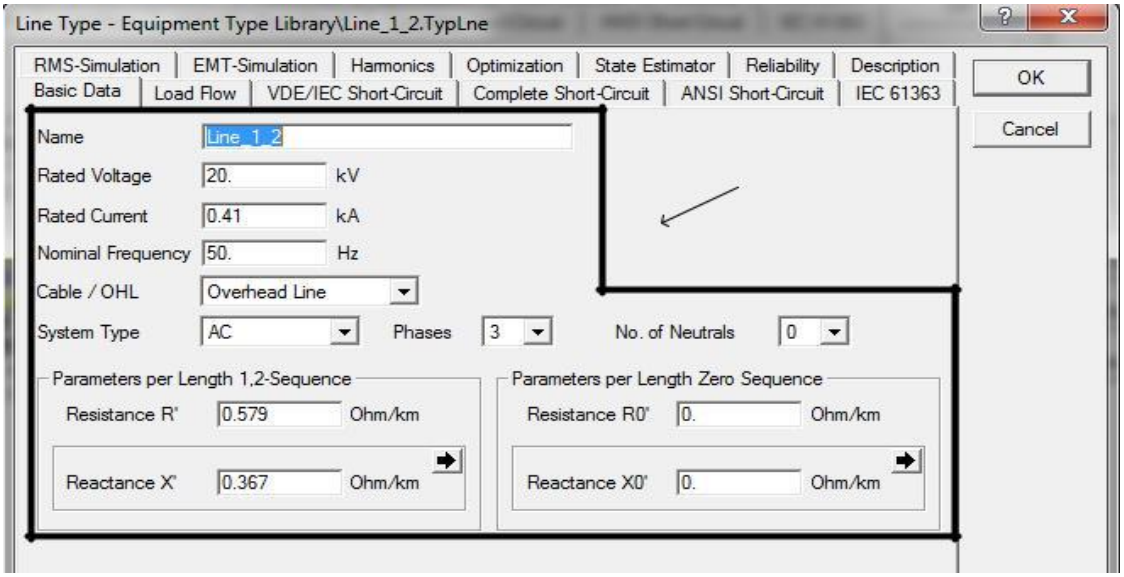
Please Select 'Line Type' - Library\Equipment Type Library :

- Database
  - Configuration
  - Library
  - System
  - Demo
  - Markos
    - CIGRE MV Benchmark
    - **CIGRE MV Benchmark(1)**
      - Library
        - Equipment Type Library
          - Scale
        - Operational Library
        - Scripts
        - Templates
        - User Defined Models
      - **Network Model**
      - Operation Scenarios
      - **Study Cases**
      - Settings
    - CIGRE MV Benchmark(2)
    - CIGRE MV Benchmark(3)
    - DPL ReadWriteFile

Name	Type
Line_10_11	
Line_12_13	
Line_13_14	
Line_1_2	
Line_2_3	
Line_3_4	
Line_3_8	
Line_4_11	
Line_4_5	
Line_5_6	
Line_6_7	
Line_7_8	
Line_8_9	
Line_9_10	

Ln 4 | 14 object(s) of 18 | 1 object(s) selected

Figure 5-a: Transmission line profiles



Line Type - Equipment Type Library\Line_1_2.TypLne

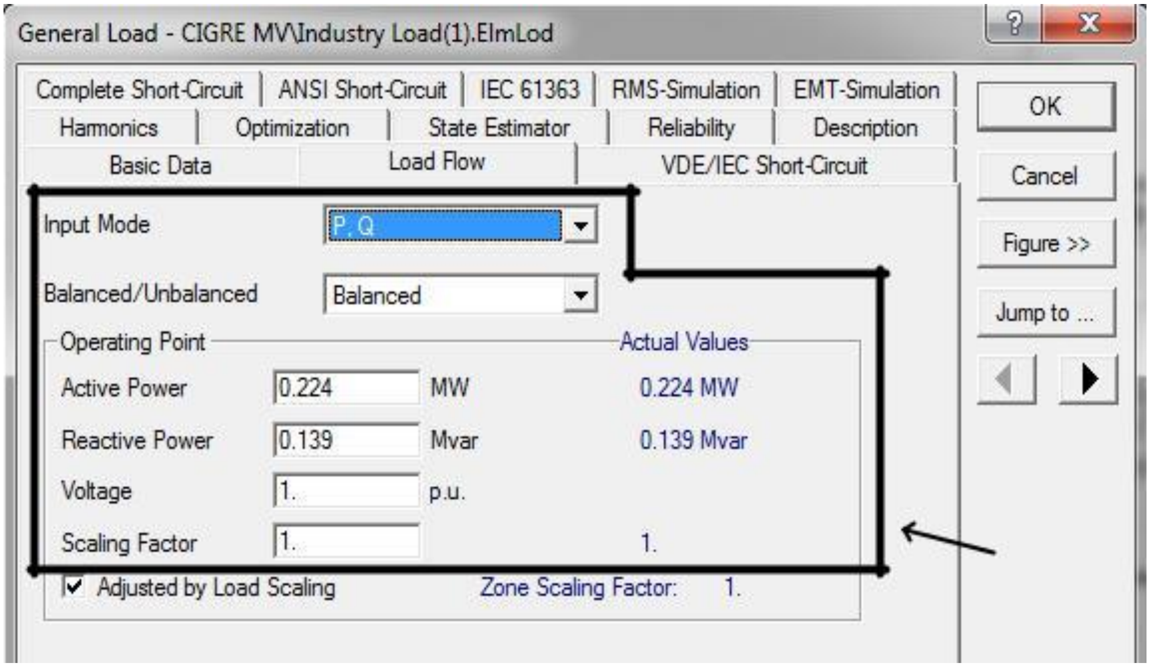
Name: Line_1_2
Rated Voltage: 20. kV
Rated Current: 0.41 kA
Nominal Frequency: 50. Hz
Cable / OHL: Overhead Line
System Type: AC
Phases: 3
No. of Neutrals: 0

Parameters per Length 1,2-Sequence
Resistance R': 0.579 Ohm/km
Reactance X': 0.367 Ohm/km

Parameters per Length Zero Sequence
Resistance R0': 0. Ohm/km
Reactance X0': 0. Ohm/km

Figure 5-b: Transmission lines Indicative Input Values

In order to represent consumptions in a grid model, “Load” element needs to be used. A load element can represent one very high load or aggregated smaller loads connected in the same node. There are several ways for setting the input mode of a load in DIgSILENT. There is a possibility to set it according to P,Q values, this way is a straight forward way and in most cases those two values are known, also for load flow calculations P,Q needs to be known. On the other hand, there is a possibility to set the input mode by using P,cos(φ) or Q, cos(φ) and afterwards DIgSILENT extracts P,Q values by e.g. power triangle [7]. All settings are presented in **Figure 6**.



General Load - CIGRE MV\Industry Load(1).ElmLod

Input Mode: P,Q

Balanced/Unbalanced: Balanced

Operating Point			Actual Values
Active Power	0.224	MW	0.224 MW
Reactive Power	0.139	Mvar	0.139 Mvar
Voltage	1.	p.u.
Scaling Factor	1.		1.

☑ Adjusted by Load Scaling

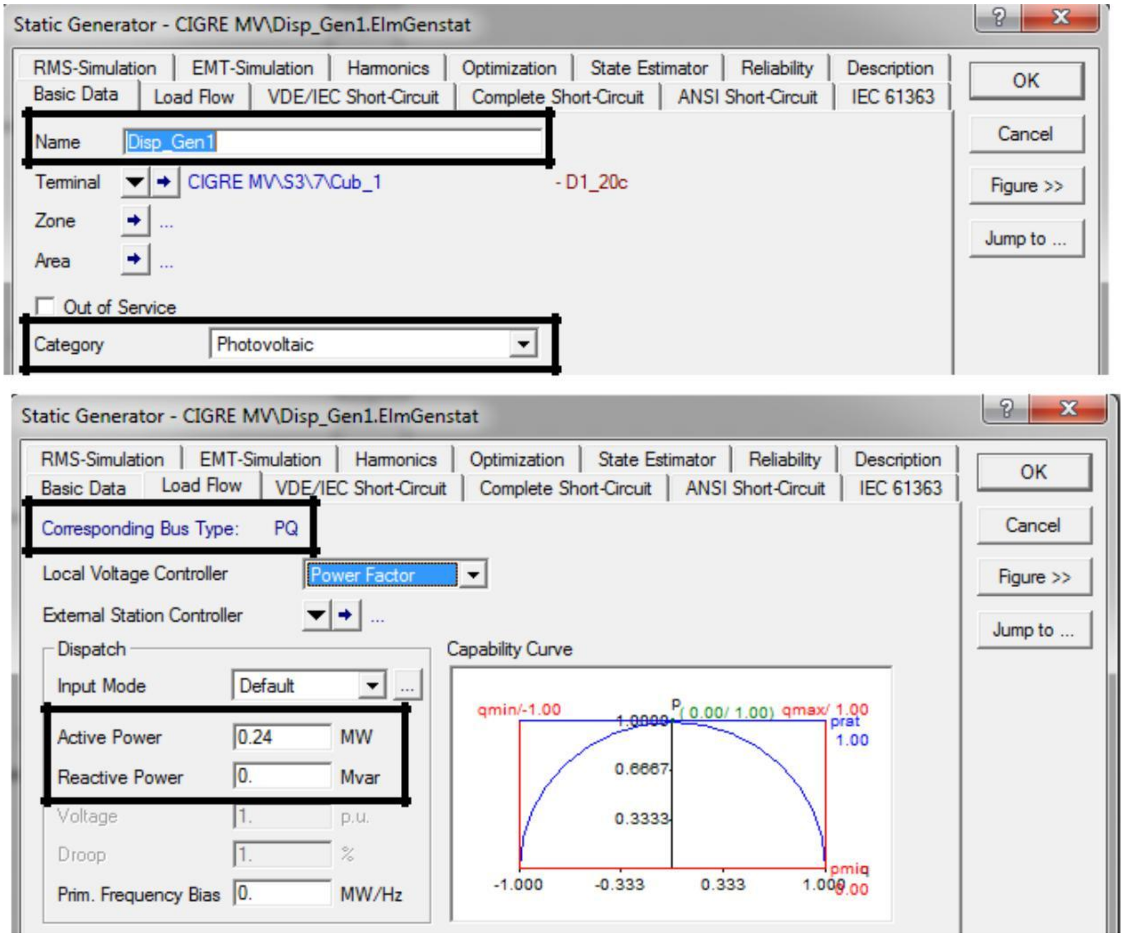
Zone Scaling Factor: 1.

Figure 6: Mandatory settings for "Load" element

For representation of dispersed generation in a grid model there are several ways of implementation. One possible way could be by means of Load elements with the significant difference that instead of positive active power, negative active power needs to be assigned, this modification makes sure that load flow will be executed properly.

Another more appropriate way is by means of “Static generator” elements [8]. Those elements are available in DIgSILENT and according to type of dispersed generation e.g. Photovoltaic, Wind turbine, etch. the field “Category” can be modified (**Figure 7**).

Other inputs needed for this grid element is name, active power and reactive power due to correspondence to P, Q bus (input fields can be seen in **Figure 7**). In addition, user has the ability to build it “Project type” like all prior mentioned elements but this is not a convenient option due to differences in every DG unit.



Static Generator - CIGRE MV\Disp_Gen1.ElmGenstat

Name: Disp_Gen1

Terminal: CIGRE MV\S3\7\Cub_1 - D1_20c

Zone: ...

Area: ...

☐ Out of Service

Category: Photovoltaic

Static Generator - CIGRE MV\Disp_Gen1.ElmGenstat

Corresponding Bus Type: PQ

Local Voltage Controller: Power Factor

External Station Controller: ...

Dispatch

Input Mode: Default

Active Power: 0.24 MW

Reactive Power: 0. Mvar

Voltage: 1. p.u.

Droop: 1. %

Prim. Frequency Bias: 0. MW/Hz

Figure 7: Input fields for "Static generator" element

After the end of building a grid model, it is time to perform simulations in order to analyze its behavior. Those simulations are realized by means of load flow calculations in order to determine the quantities P, Q, |V|, δ for every node of the system. A LDF calculation is a steady state calculation and non-faulted conditions are assumed.

In order to perform LDF calculation in DIgSILENT, it can be done once manually (**Figure 8**) or it can be done automatically and multiple times by using DPL script.

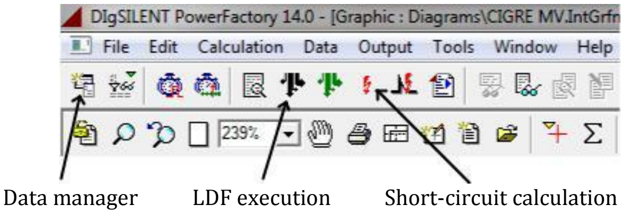


Figure 8: Data manager, LDF execution and Short-circuit calculation buttons are depicted

The programming part of DIgSILENT, gives to user extra abilities compare to the designing part. Designing part is mostly determined for manual modifications in the model and calculations which need to be done few times, in case of existence of long term data (instead of only one set), they can be imported in DIgSILENT trough DPL script and actions can be taken iteratively. DPL script is based on programming language "C" and it can be accessed through "Data manager".

After import of data, proper commands need to be used in order to perform modifications on each element of the implemented grid model. For instance, it is possible to be available a file with load profile for one day, then through DPL script, each value of load profile can be imported and replace a value of a load element which exists in the grid model. Then, for every load profile value, a LDF can be executed and see the response of the grid e.g. busvoltage variation, transmission line loading, etch.

Another advantage of DPL script is the ability of saving data, e.g. results or any other useful information can be saved in files and then used for any purpose. Supported file formats are text files (.txt) and excel files (.csv), this means that there are compatible with most popular software such as MATLAB.

At this point, some vital commands of DPL script concerning grid elements are going to be presented, for the grid element "Transmission line", commands are going to be presented in analytical form and then, for the rest of the elements in compact form:

Transmission line

TL.A. Lines =AllRelevant('*.ElmLne'); – This command locates all transmission line elements and saves them in a vector called "Lines".

TL.B. Lines.SortToVar(0,'loc_name'); – In this case, vector "Lines" is re-arranged according to alphabetic order. Command "'loc_name" can be used in a similar way for the rest of grid elements.

TL.C. i = O.VarExists('dline'); – The objective in this command is to locate the length of a transmission line and save it in "i".

TL.D. varOkL = OLine.VarExists('c:loading'); – By variable "c:loading", loading of a transmission line is determined and saved in "varOkL".

Load

L.A. ElmLod – Through "ElmLod" all load elements are located, the structure is similar to

TL.A.

L.B. oTemp:plini=dP1; – In this case, a value for real power has been read from e.g. a file, and is stored as real power ("plini") in a load element of the grid.

L.C. oTemp:qlini=dQ1; – Similar case to **L.B.** but instead of real power, reactive power is stored.

Static generator

SG.A. ElmGenstat – All static generator elements are located (similar syntax to **TL.A.**). **SG.B.** oTemp:pgini=dP19; - A real power value taken from e.g. a file replaces a real power value ("pgini") of a static generator connected in the grid model (similar to **L.B.**).

SG.C. oTemp:qgini=dQ19; - In case reactive power from e.g. a file needs to replace a value of reactive power ("qgini") in a static generator, it can change using this syntax.

Terminal

T.A. ElmTerm – All existing terminals are located through "ElmTerm" (similar syntax to **TL.A.**).

T.B. Name of each terminal is located according to **TL.B.**

T.C. m:u – Voltage of each terminal is located. For structure of the command see **TL.D.**

Transformer

TR.A. ElmTr2 – Locates all 2-winding transformers existing in the grid (similar syntax to **TL.A.**).

TR.B. In order to locate the name of a transformer, syntax is according to **TL.B.**

TR.C. TransformerCount=Transformers.Count(); – By this command, transformers are counted. This command can apply to all grid elements.

TR.D. Loading of a transformer can be determined in an identical way to **TL.D.**

LDF

In order to perform LDF in DPL script two commands are needed:

LDF.A. Ldf=GetCaseObject('ComLdf'); – Link a variable with LDF command.

Where:

'ComLdf' – Load flow command in DPL script.

Ldf – Variable name used to link the LDF command.

LDF.B. Ldf.Execute(); – This command executes the LDF

Reading – writing from/to file

RW.A. fopen('C:\DIgSILENT\HL_PQ.csv','r',0); – This command sets the path and opens a reading file from the hard disk.

RW.B. fopen('C:\DIgSILENT\Resulted_BusV_1.csv','w',3); – This command sets the path and opens a writing file from the hard disk.

RW.C. fclose(n); - Every “fopen” has to close with one “fclose” where n is the number of the file corresponding to “fopen”.

As mentioned in previous paragraphs, DPL script is based on “C” language, therefore, Reading – writing from/to file is similar to “C” reading-writing (as it can be seen in the example above). In order to conclude with DPL script, it needs to be said that iterative loops can be established, such as “for” command or “do-while” command or any other command existing in “C” can be used. Iterative loops are not presented in this chapter as their structure is identical to “C”.