A PROPOSED RULE FOR THE INTERCONNECTION OF DISTRIBUTED GENERATION AND ITS ECONOMIC JUSTIFICATION

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ABSTRACT

A PROPOSED RULE FOR THE INTERCONNECTION OF
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Distributed generation (DG) is electricity generation by small generating units, which are interconnected at distribution level with capacity less than 50 MW. Environmental concerns and the idea of using cheap and domestic renewable resources increased the popularity of DG following the developments in equipment technology. In Turkey, interconnection of DG is realized through the distribution busbars of 154/36 kV substation. The interconnection of DG at 36 kV feeders is not allowed by distribution system authority. This thesis proposes an interconnection rule which includes technical analyses to be conducted before the permission of interconnection of DG at 36 kV feeders. Moreover, the protection functions and operational requirements needed for the proper and safe operation of distribution system in presence of DG are introduced. A sample distribution system with relevant parameters is used for the simulation studies in Digsilent software. In order to determine the operational reserve requirement against the variations in wind generation, a statistical method including Weibull distribution, standard deviation and monthly average wind speeds is used. Convenience of hydropower plants' response for being backup generation against the fluctuations in wind generation is analyzed by a mid-term dynamic model of the power system. A secondary control mechanism for the integration of wind power is suggested. Finally, an economic comparison between the interconnection alternatives of hydropower and photovoltaic power plants at the distribution busbar of the 154/36 kV substation and the 36 kV feeder is done by present worth analysis using the up to date power plant costs and incentives.

Keywords: Distributed Generation, Technical Analyses, Protection and Interconnection Requirements, Operational Reserve Requirement, Present Worth Analysis

ÖZ

DAĞITIK ELEKTRİK ÜRETİMİNİN ŞEBEKE BAĞLANTISI İÇİN ÖNERİLEN BİR YÖNETMELİK VE BU YÖNETMELİĞİN EKONOMİK OLARAK DOĞRULANMASI

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Dağıtık elektrik üretimi (DEÜ), dağıtım seviyesinden şebekeye bağlanan ve kurulu gücü 50 MW'ın altında olan küçük ünitelerden elektrik üretimidir. Malzeme teknolojisindeki gelişmelerin ardından, çevresel kaygılar ile ucuz ve yerli yenilenebilir kaynaklardan elektrik üretme fikri, DEÜ'nin popülaritesini arttırmıştır. Türkiye'de, DEÜ'nin şebeke bağlantısı 154/36 kV indirici merkezin dağıtım baralarından gerçekleştirilmektedir. 36 kV fiderlerden DEÜ bağlantısına dağıtım sistemi otoritesi tarafından izin verilmemektedir. Bu tez, DEÜ'nin 36 kV fiderlerden bağlantısının izninden önce yapılması gereken teknik analizleri içeren bir bağlantı yönetmeliği önermektedir. Ayrıca, DEÜ varlığında dağıtım sisteminin doğru ve güvenli işletilmesi için ihtiyaç duyulan koruma ve işletme gereksinimleri de sunulmaktadır. Digsilent yazılımında yapılan benzetim çalışmaları için ilgili değişkenleri ile birlikte örnek bir dağıtım sistemi kullanılmıştır. Rüzgar üretimindeki değişikliklere karşı ihtiyaç duyulan işletme rezerv gereksiniminin belirlenmesi için, Weibull dağılımı, standart sapma ve aylık ortalama rüzgar hızlarını içeren istatistiksel bir yaklaşım kullanılmıştır. Rüzgardan elektrik üretimindeki dalgalanmalar için, hidroelektrik santrallerin yedek üretim olarak kullanımının uygunluğu, güç sisteminin orta-vadeli dinamik modeli ile analiz edilmiştir. Rüzgar santrallerinin entegre edilmesi için bir sekonder kontrol mekanizması önerilmiştir. Son olarak, güncel santral maliyetleri ve teşvikler kullanılarak şimdiki değer analizi ile hidroelektrik ve fotovoltaik santrallerin 154/36 kV indirici merkezin dağıtım barasından ve 36 kV fiderden bağlanma seçenekleri arasında ekonomik bir karşılaştırma yapılmıştır.

Anahtar Kelimeler: Dağıtık Elektrik Üretimi, Teknik Analizler, Koruma ve Bağlantı Gereksinimleri, İşletme Rezerv Gereksinimi, Şimdiki Değer Analizi

To My Parents

My Sister

My Brother

and My Fiancée

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CHAPTER 1

INTRODUCTION

1.1 Distributed Generation

In the very first supply systems, electric generators were built very close to the loads to be fed and there was a very simple network to connect the generator and loads to each other. But as the demand got larger, it had been necessary to establish a nationwide grid, where power generated in central power plants and transported to loads via transmission lines. The idea of distributed generation (DG), which refers to generation units connected to the distribution system, became popular in 1990's with the environmental concerns and the assessment of renewable energy resources as the source of cheap and domestic electricity generation. In recent years, the transmission and distribution costs have increased, while the costs of DG units have decreased. The primary benefit of DG is that DG reduces the transportation costs significantly since the power is consumed where it is generated. In addition, increasing the security of energy supplies by reducing the dependency on imported fossil fuels such as oil and natural gas, and reducing the emission of greenhouse gases, especially carbon dioxide, emitting from the burning of fossil fuels are two important goals for the countries which increase the penetration of DG in their systems [1]-[3].

Today, advances in new materials and design for photovoltaic cells, reciprocating engines, microturbines, fuel cells, control and protection systems and remote monitoring devices have expanded the range of applications in DG. DG could be used in applications such as autonomous power system with compensation of reactive power, compensation of power quality events, correction of power factor, shaving of peak loads and providing backup generation. The increase in reliability and efficiency in DG technologies have make the usage of these technologies possible in power system market after the liberalization of electricity market which looks for efficient and cheap electricity resources [4]-[6].

The interest of investor on DG has increased as the decreasing prices of DG technologies have made them affordable. The need of investment for constructing a DG facility is relatively small compared with the central power stations. Nowadays, people are considering the construction of small generation units such as wind or photovoltaics at their homes for supplying the needs of their house appliances and selling the extra energy to grid at the secondary circuit.

This trend on DG will bring some technical and operational difficulties beyond the important benefits. The distribution system engineers, planners, operators are working on this issue for guaranteeing the quality and continue of power supply.

1.2 Objectives and Motivation

Trend in energy investments shows that penetration of DG in distribution system will increase sharply in coming years. The environmental concerns and the willingness of relatively small investors compared with the ones of central power stations will make DG issue more important in the next decade in Turkey. The problem in this conjuncture is that the necessary regulations for the interconnection of DG to the distribution system have not been defined yet. This is due to the fact that distribution system authority could not venture this new situation, with the belief that the presence of DG in distribution system will ruin the safety and quality of the supply. Therefore, small generation units are connected to the grid at the distribution side of the high-voltage (HV) substation, which brings an extra cost for the investors. Although there is an increasing tendency towards the investment on DG, the lack of the interconnection regulation and insufficient incentives delays the possible investments on this area. Moreover, as the penetration of renewable resources, whose output power could not be estimated such as wind power, increases, the operational reserve determination methods should be renewed according to the new power system structure.

The main objective of this thesis is to obtain an interconnection rule for DG in which the requirements of connection of DG units to the utility at distribution system level. For this purpose, relevant technical and operational analyses will be conducted and the necessary analyses for the preparation of the interconnection rules will be selected. The aim is to reduce the interconnection of DG while retaining the requirements of a proper power system operation.

1.3 Scope of the Thesis

In this thesis, a rule for the interconnection of DG at the distribution system level is prepared and operation, protection and interconnection requirements of DG units are listed. Then, the amount of required reserve for wind generation is found by probabilistic approach. Later, convenience of hydropower plants as backup generation against wind power fluctuations is investigated. Finally, by an economic analysis, the benefit of the interconnection alternative proposed by considering the rule and the requirements is explained in monetary terms. In order to accomplish these objectives, the methodology followed in this thesis could be summarized as below:

a. <u>Determining the generator types and parameters of a sample distribution system</u>: In DG applications, there are different types of generators used. Relevant data of these types of generators have been collected. Moreover, the parameters and elements of the distribution system which will be used as sample distribution system have been determined.
b. <u>Preparing simulation medium with a power system analysis software</u>: A simulation medium is needed to do relevant analyses of DG. For this purpose, DigSilent power system analysis software has been used. With the power system elements' models, a sample distribution system model has been created inside the program along with the DG models.

c. <u>Conducting technical analyses of different impacts of distributed generation</u>: There are different technical impacts of the presence of DG in the distribution system. Within the simulation medium, various simulation functions such as load flow, fault analysis have been used for conducting technical analyses of the sample system with DG.

d. <u>Determination of required reserve with the presence of wind turbines distributed geographically in power system</u>: The uncertainty in the power output of wind turbines could not be estimated, therefore, the reserve kept for these plants is nearly as much as the installed capacity of these facilities. In order to investigate the effect of geographical distribution of these plants, the outputs of different wind power plants have been obtained by probabilistic approach. The required reserve has been determined in each case for increasing the amount of dispersion of wind power plants with statistical methods.

e. <u>Investigating whether the usage of hydropower plants for compensating the changes in wind power is convenient</u>: The necessary time for the hydropower plants to take load is determined by the time constants of plant components, such as power controller, governor and turbine. These components have been modeled in a network composed of only hydropower and wind generation. Later, the model is enlarged by modeling thermal and gas power plants and the effect of fluctuations in wind generation is compensated by thermal, gas and hydropower plants with the secondary controller sending target generation points to each of them. Finally, a wind secondary controller design is evaluated in the general power system model.

f. <u>Creating the rule, protection and interconnection requirements</u>: After the analyses have been completed, the necessary analyses have been selected among them in order to give authorization for the connection of DG facilities to the utility at the distribution level. With the selected analyses, a rule for the connection has been created. Then, the equipment needed for the safe and proper operation of the grid and DG units have been listed in protection and interconnection requirements.

g. Determining the parts and costs of distribution system including distributed generation: In order to evaluate the economic benefits of the alternative connection type approved by the rule, the parts and costs of each part of the distribution system in presence of DG need to be defined.

h. Performing an economic analysis of interconnection alternatives: An economic analysis for the financial comparison of two different interconnection alternatives for hydropower plants and photovoltaic power plants has been performed using the present worth analysis.

i. Evaluation of the results: Finally, the results that have been obtained from the studies done in this thesis have been evaluated and the conclusion of the thesis has been written.

1.4 Thesis Outline

In Chapter 2, a general background about definition, benefits and resources of DG, technologies used in DG applications and future power system are given. Chapter 3 includes the relevant technical and operational impact analyses for the interconnection of DG units and a list of requirements to be satisfied before permitting the interconnection of DG. The parts and costs of distribution system and the economic analysis for the interconnection alternatives of different types of DG applications are explained in Chapter 4. Finally, in Chapter 5, the thesis is concluded. The detailed explanations of relevant issues are provided in Appendices.

CHAPTER 2

GENERAL BACKGROUND

2.1 Definition of Distributed Generation

Today, much of the electrical energy is generated by large-scale, centralized power plants using fossil fuels (coal, oil and gas), hydropower or nuclear power, with energy being transmitted and distributed over long distances to consumers. As seen in Figure 1, power flows only in one direction: from the central power stations to the network and to the consumers [7].

There are a number of drawbacks of such a system, such as the high level of dependence on imported fuels, the environmental impact of greenhouse gases and other pollutants, transmission losses and the necessity for continuous upgrading and replacement of transmission and distribution facilities.

In contrast, in a power system composed of distributed energy resources, much smaller amounts of energy are produced by numerous small, modular energy conversion units, which are often located close to the point of end use, as could be seen in Figure 2. These units can be stand-alone or integrated into the electricity grid.

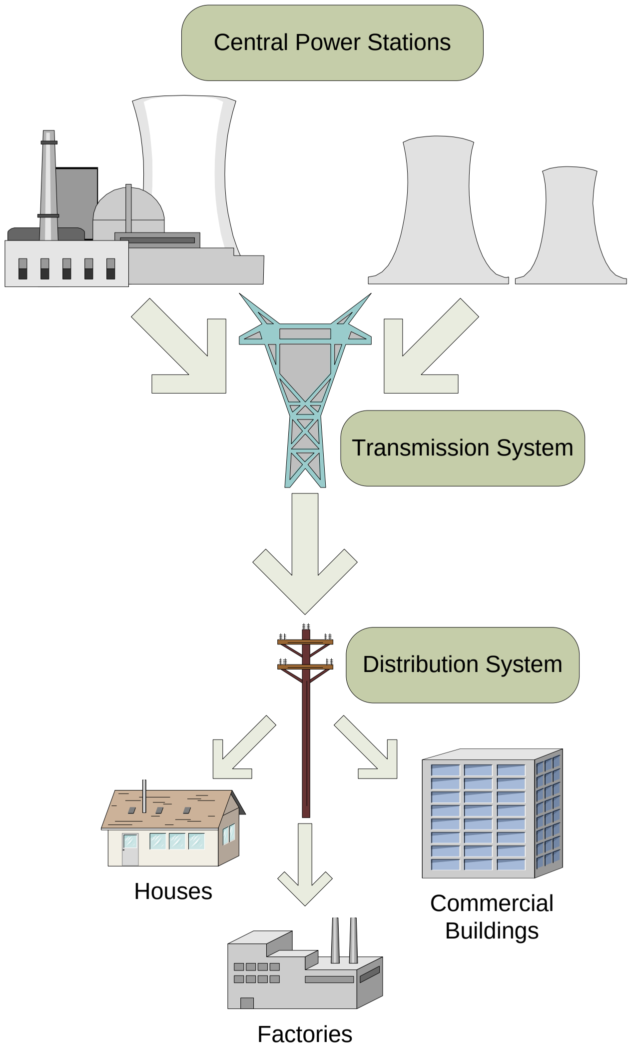

Figure 1 Power flow from central power stations to the customers

There are many definitions declared by different international and regional institutes. Some of these definitions have been listed below:

a. Institute of Electrical and Electronic Engineers (IEEE): IEEE defines DG as electric generation facilities connected to an Area Electric Power System (Area EPS) through a Point of Common Coupling (PCC); a subset of distributed resources (DR). In this definition, Area EPSs are the facilities that deliver electric power to Local EPSs. These local EPSs could contain generation units, as well. Each Local EPS could contain a single premises or group of premises. The point where a Local EPS is connected to the Area EPS is called the point of common coupling. Finally IEEE defines distributed resources as sources of electric power that are not directly connected to a bulk power transmission system. DR includes both generator and energy storage technologies [8]. Figure 3 visualizes the definition of IEEE.

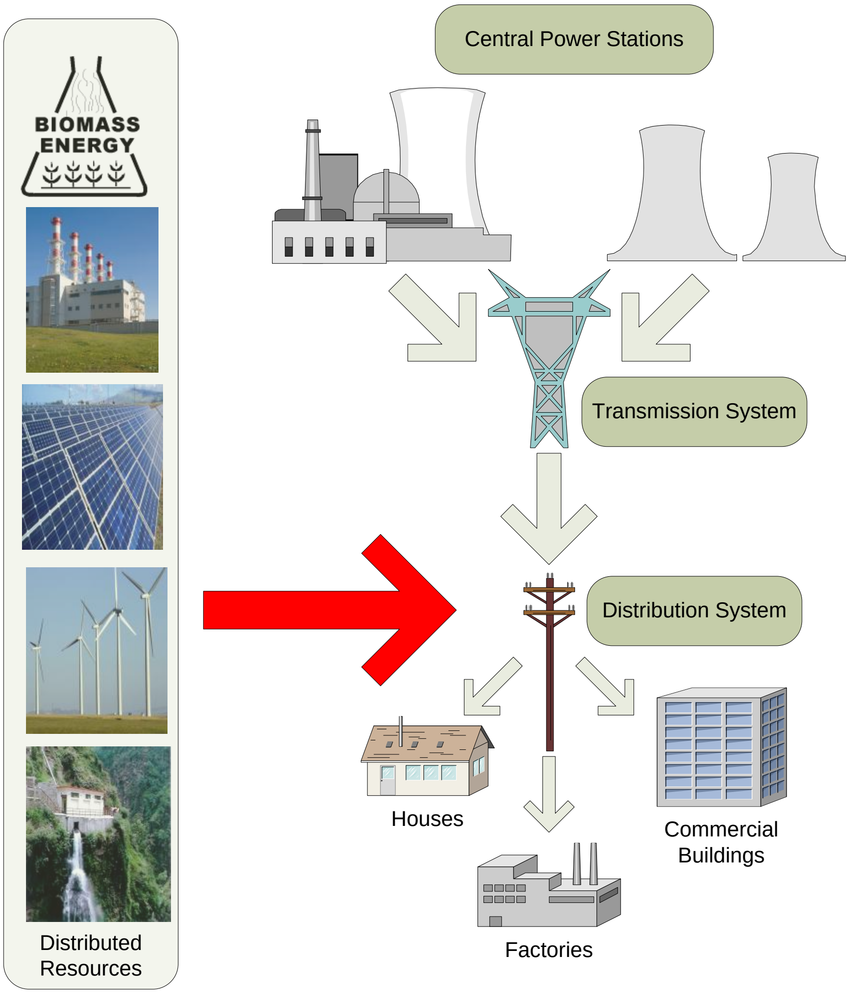

Figure 2 Power flow with DG

b. <u>International Council on Large Electric Systems (CIGRE)</u>: CIGRE Work Group 37-23 defines the definition of DG as [9]:

- Not centrally planned
- Today not centrally dispatched
- Usually connected to the distribution network
- Smaller than 50-100 MW.

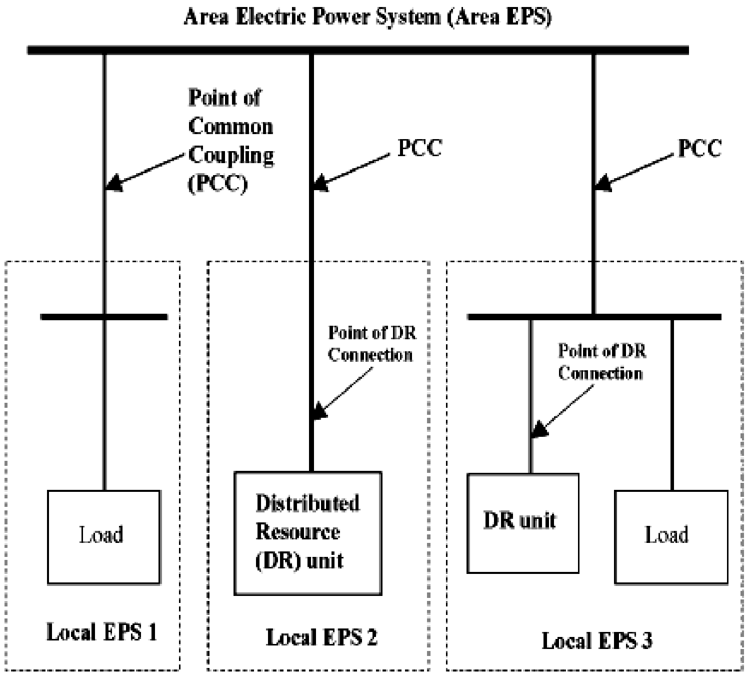

Figure 3 Schematic of IEEE DG definitions

c. The U.S. Department of Energy (DOE): Distributed power is modular electric generation or storage located near the point of use. Distributed systems include biomass-based generators, combustion turbines, thermal solar power and photovoltaic systems, fuel cells, and turbines, microturbines, engines/generator sets, and storage and control technologies. Distributed resources can either be grid connected or independent of the grid. Those connected to the grid are typically interfaced at the distribution system [10].

d. The Electric Power Research Institute (EPRI): EPRI considers small generation units from a few kW up to 50 MW and/or energy storage devices typically sited near customer loads or distribution and sub-transmission substations as distributed energy resources [11].

In another definition, DG is defined as the utilization of small (0 to 5 MW), modular power generation technologies dispersed throughout a utility's distribution system in order to reduce transmission and distribution (T&D) loading or load growth and thereby defer the upgrade of T&D facilities, reduce system losses, improve power quality, and reliability [12]. In some countries, a strict definition of DG is made, based either on the rating of the plant or on the voltage level to which DG is connected [13].

Although there is no universally accepted definition for DG, following criteria would be helpful for understanding the concept of DG:

a. Voltage Level at Grid Connection: General idea on the voltage level for the connection of DG to the grid is that DG should be connected to the distribution network, either on the distribution or on the consumers' side of the meter. Actually, DG should be located closely to the load. Since there is no common voltage level for distribution all over the world, it is not possible to determine a certain voltage level for DG. So, it would be more appropriate to use the distribution network level for the voltage level.
b. Generation Capacity: As seen in the above definitions, there is no agreement on maximum generation capacity levels for DG. Since the amount of the generation depends on the capacity of the grid to be connected, the generation capacity of DG is not determined independently from the grid conditions. Although the generation capacities of the distributed generators affect some technical issues such as steady-state voltage profile and short-circuit current contribution, generation capacity is not a relevant criterion for defining DG.
c. Services Supplied: DG units should at least supply active power to the grid. The supply of reactive power and other ancillary services are not necessary.
d. Primary Source: The primary source for DG is commonly thought to be renewable, but many DG technologies use non-renewable sources. So, the primary source is not considered for the definition of DG.
e. Operation Mode: Operation mode includes generation is whether scheduled, subject to pool pricing and dispatchable. Within these conditions, DG is defined with being undispatchable.

f. Power Delivery Area: In some cases, DG is described as power that is generated and consumed within the same distribution network. This expression requires power flow analysis. Instead, it is convenient to define DG as generation close to the load [14].

Considering the above criteria, it could be concluded as DG, also called on-site generation, dispersed generation, embedded generation, decentralized generation, decentralized energy or distributed energy [15], is the electricity generation from many small energy sources which could be stand-alone or connected to the grid at the distribution level.

2.2 Benefits of Distributed Generation

The penetration of DG into distribution network brings lots of benefits for the customers, suppliers and the society.

2.2.1 Customer Benefits

a. Reliability Improvement: DG improves the reliability and security of the supply, especially for those customers who carry out sensitive activities with high interruption costs (banks, hospitals, etc.). DG installed for this purpose operates primarily in stand-by as back-up power ready to operate in case of emergencies or utility supply interruptions [16].
b. Reduced Electricity Bills: Installing DG is a good choice for customers who want to reduce their electricity bills, especially for combined heat and power (CHP) applications. The idea is to generate electricity locally at lower costs compared with the utility rates.
c. Micro-grid Application: With various DG technologies, it is possible to provide a stand-alone power option for areas where transmission and distribution infrastructure does not exist or very expensive to build. In Figure 4, a sample application for micro-grid could be seen.

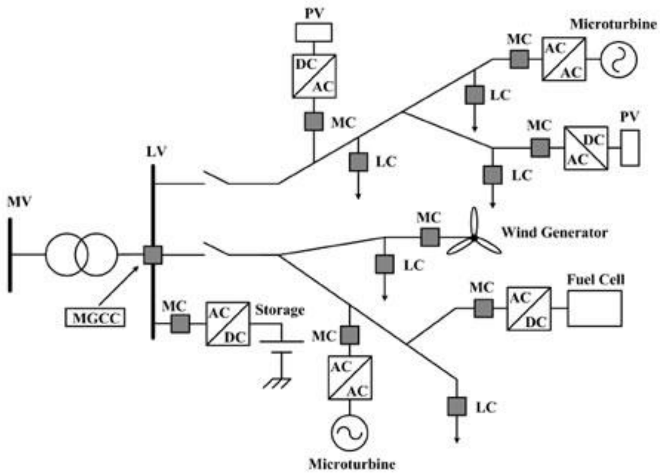

Figure 4 A sample micro-grid application

2.2.2 *Supplier Benefits*

a. Limiting Capital Cost and Risks: DG limits capital exposure and risk because of the size, location flexibility, and rapid installation time afforded by the small, modularly constructed, environmentally friendly and fuel flexible systems.
b. Transmission and Distribution Capacity Deferral: DG avoids major investments in transmission and distribution system upgrades by locating new generation near the customer.
c. Generation Capacity Deferral: DG defers or avoids capital investment in central generation capacity by providing new generation capacity close to the load [17].
d. Avoided Electricity Purchases: Distribution utilities guarantee the electricity supply to customers by purchasing power from the wholesale market through both, long-term bilateral forward contracts with generators or brokers and the short-run spot electricity market. During the hours where the electricity prices are the highest (during peak load or generation scarcity), it may be cost-effective for the distribution utilities to aggregate and purchase the electricity produced by customer-owned DGs.
e. Loss Reduction: The ability of DG to reduce distribution network losses has been widely recognized by the industry. If the total DG output in a

given feeder does not exceed the local demand, currents will be reduced and so will the losses.

f. Improvement in Voltage Control/VAR Control: Some DG technologies provide voltage/VAR control, thus helping the power quality that the supplier guarantees for the customers.

g. Reducing the Need of Ancillary Services: DG decreases the need for the spinning reserve, regulation, standby capacity or peak use capacity or other ancillary services.

2.2.3 Society Benefits

a. Electricity Market Price Reduction: The widespread implementation of DG technologies over a broad area or region accounting for several hundreds of MW may have an impact on the wholesale electricity prices. In the electricity markets, generating units are usually dispatched from the cheapest to the most expensive until the total generating capacity meets the expected demand. Therefore, any demand reduction with respect to a known level will be reflected, at least theoretically, on a slight reduction in market prices.

b. Environmental Concerns: DG technologies that rely on renewable energy sources could yield environmental benefits in the form of reduced emissions of pollutants and greenhouse gases if those technologies displaced utility-supplied power, much of which is generated from coal. High-efficiency technologies could yield benefits by reducing the amount of energy required to produce a unit of electricity. As part of the Kyoto Protocol, Turkey has to reduce emissions of CO_2 substantially to help counter climate change.

c. Efficient Use of Cheap Fuel Opportunities: Installing DG allows the exploitation of cheap fuel opportunities. For example, in the proximity of landfills, DG units could burn landfill gasses.

d. Diversification of Energy Sources: As known, DG primary energy resources are renewable resources like wind, solar and hydro and non-renewable sources like bio-mass, diesel or gas. With the diversification of the energy sources, the reliability of the whole system is increased. Also, domestic sources like wind, geothermal and bio-mass decreases the import of foreign sources like oil and gas [14].

2.3 Distributed Energy Resources

Distributed energy resources (DER) have been available for many years. They may have been known by different names such as generators, back-up generators, or on-site power systems, and certain DER technologies are not new (e.g., internal combustion engines and combustion turbines). On the other hand, due to the changes in the utility industry, several new technologies are being developed for commercialization (e.g., fuel cells and microturbines) [18]. There are several energy resources that drive distributed generators as explained in detail below:

2.3.1 Reciprocating Engines

Reciprocating engines are the most common and most technically mature of all DER technologies. Reciprocating engines use commonly available fuels such as gasoline, natural gas, and diesel fuel. A reciprocating, or internal combustion (IC), engine converts the energy contained in a fuel into mechanical power. IC engine generators for distributed power applications, commonly called gensets, are found universally in sizes from less than 5 kW to over 7 MW. Gensets are frequently used as a backup power supply in residential, commercial, and industrial applications. They have the lowest first costs among DER technologies [15]. The strengths and weaknesses of reciprocating engines have been listed in Table 1.

Table 1 Strengths and weaknesses of reciprocating engines

Reciprocating Engines	
Strengths	**Weaknesses**
Low capital cost	Atmospheric Emissions
Good electrical efficiencies (up to 45%)	Noisy
Quick startup	Frequent maintenance intervals
Fuel Flexibility	
High Reliability	
Low natural gas pressure required	

2.3.2 *Combustion Turbine*

Conventional combustion turbine (CT) generators are a very mature technology. They typically range in size from about 500 kW up to 25 MW for DER and up to approximately 250 MW for central power generation. They are fueled by natural gas, oil, or a combination of fuels. Small combustion turbines are found in a broad array of applications including mechanical drives, base load grid-connected power generation, peaking power, and remote off-grid applications.

Combustion turbines are available in a wide range of sizes (500 kW - 25 MW) with most commercial products falling in the 1 - 7 MW size range [18]. Gas turbines are relatively inexpensive compared with other DER technologies. The strengths and weaknesses of combustion turbines have been listed in Table 2.

Table 2 Strengths and weaknesses of combustion turbines

Combustion Turbines	
Strengths	**Weaknesses**
High efficiency and low cost (particularly in large systems)	Reduced efficiencies at part load
Readily available over a wide range of power output	Sensitivity to ambient conditions (temperature, altitude)
Capability of producing high-temperature steam using exhaust heat	Small system cost and efficiency not as good as larger systems
Marketing and customer servicing channels are well established	
High power-to-weight ratio	
Proven reliability and availability	

2.3.3 *Microturbines*

Microturbines are small combustion turbines that produce between 25 kW and 500 kW of power. Microturbines were derived from turbocharger technologies found in large trucks or the turbines in aircraft auxiliary power units (APUs). Microturbines can be used for stand-by power, power quality and reliability, peak shaving, and cogeneration applications.

Table 3 Strengths and weaknesses of microturbines

Microturbines	
Strengths	**Weaknesses**
Small number of moving parts	Low fuel to electricity efficiencies
Compact size	Loss of power output and efficiency with higher ambient temperatures and elevation.
Light-weight	Small system cost and efficiency not as good as larger systems
Good efficiencies in cogeneration	
Low emissions	
Can utilize waste fuels	
Long maintanance intervals	

Microturbines produce between 25 and 500kW of power and are well-suited for small commercial building establishments such as: restaurants, hotels/motels, small offices, retail stores, and many others. Commercial microturbines used for power generation range in size from about 25 kW to 500 kW. Microturbine capital costs range from $700/kW for larger units to approximately $1,100/kW for smaller ones [18]. The strengths and weaknesses of microturbines have been listed in Table 3.

2.3.4 Fuel Cells

A fuel cell is similar to a battery in that an electro-chemical reaction is used to create electric current. Fuel cells are named based on the type of electrolyte and materials used. Because individual fuel cells produce low voltages, fuel cells are stacked together to generate the desired output for DG applications. There are fuel cell types like proton exchange membrane fuel cells (PEMFC), phosphoric acid fuel cells (PAFC), solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC). These cells are used in medical, industrial, commercial and cogeneration applications. The first cost of fuel cells is very high compared to those of other DER technologies [18]. The strengths and weaknesses of fuel cells have been listed in Table 4.

Table 4 Strengths and weaknesses of fuel cell types

	Fuel Cells			
	PAFC	MCFC	SOFC	PEMFC
Strengths	Quiet	Quiet	Quiet	Quiet
	Low emissions	Low emissions	Low emissions	Low emissions
	High efficiency	High efficiency	High efficiency	High efficiency
	Proven reliability	Self reforming	High energy density	Synergy with automotive R&D
			Self reforming	
Weaknesses	High costs	Need to demonstrate long term dependability	Planar SOFCs are still in the R&D stage but recent developments in low temperature operations show promise	Low temperature waste heat may limit cogeneration potential
	Low energy density	High cost	High cost	Limited field test experience
				High cost

2.3.5 Photovoltaic Systems

Photovoltaic (PV) cells, or solar cells, convert sunlight directly into electricity. PV cells are assembled into flat plate systems that can be mounted on rooftops or other sunny areas. They generate electricity with no moving parts, operate quietly with no emissions, and require little maintenance.

Table 5 Strengths and weaknesses of photovoltaics

Photovoltaics	
Strengths	**Weaknesses**
Work well for remote locations	Local weather patterns and sun conditions directly affect the potential of photovoltaic systems. Some locations will not be able to use solar power.
Require very little maintenance	
Environmentally friendly (no emissions)	
Low Maintenance	High Costs

Building-integrated photovoltaics (BIPV) are increasingly incorporated into new domestic and industrial buildings as a principal or ancillary source of electrical power and are one of the fastest growing segments of the photovoltaic industry. In addition to the solar array, several large photovoltaic power plants have been completed since 2008 in Spain, Portugal and North America. Currently PV systems cost between $6,000-$10,000/kW installed [15]. The strengths and weaknesses of photovoltaics have been listed in Table 5.

2.3.6 Energy Storage / UPS Systems

Energy storage technologies do not generate electricity but can deliver stored electricity to the electric grid or an end-user. They are used to improve power quality by correcting voltage sags, flicker, and surges or correct for frequency imbalances. Storage devices are also used as uninterruptible power supplies (UPS) by supplying electricity during short utility outages. There are different types of energy storage systems such as batteries, flow batteries, flywheels, superconducting magnetic energy storage systems, supercapacitors and compressed air storage systems. Unlike the other DER equipment, whose performance tends to be determined by power generation or electrical efficiency, the performance of energy storage and UPS systems is determined by the capacity and duration of the equipment. The cost of a complete UPS system can range from $200/kVA - $1500/kVA [18]. The strengths and weaknesses of energy storage/UPS systems have been listed in Table 6.

Table 6 Strengths and weaknesses of energy storage/UPS systems

Energy Storage/UPS	
Strengths	**Weaknesses**
Improved power quality and reliability	High cost for long duration storage system
"Green Power" dispatch/purchase options	Parasitic power losses to keep unit charge
Reduced sizing of DG systems (if applicable)	High maintenance (eg. frequent testing, charge assessment for batteries)
Energy/demand cost savings from load leveling	
Decreased transmission and distribution infrastructure investment	

2.3.7 Wind Turbines

Wind turbines use wind to produce electrical power. Generally, individual wind turbines are grouped into wind farms containing several turbines. Many wind farms are MW scale, ranging from a few MW to tens of MW. Wind farms or smaller wind projects may be connected directly to utility distribution systems. Wind power is a viable energy source with wide-ranging applications for DG. Wind farms can be sized for small or large-scale power generation.

Table 7 Strengths and weaknesses of wind turbines

Wind Turbines	
Strengths	**Weaknesses**
Power generated from wind farms can be inexpensive	Variable power output due to the fluctuation in wind speed
Low cost energy	Location
Minimal land use - the land below each turbine can be used for animal grazing or farming.	Visual impact - aesthetic problem of placing them in higher population density areas.
No harmful emissions	Bird mortality
No fuel required	

Wind power is becoming popular in developing countries due to the fast and simple installation and low maintenance requirements once installed. In 2009, Turkish installed wind generation capacity has reached to 1250 MW and it is planned to be 1600 MW in 2011. Large-scale wind farms can be installed for about 1,000 $/kW [19]. The strengths and weaknesses of wind turbines have been listed in Table 7.

2.3.8 Hybrid Systems

Developers and manufacturers of DER are looking for ways to combine technologies to improve performance and efficiency of DG equipment. Several examples of hybrid systems include:

- Solid oxide fuel cell (SOFC) combined with a gas turbine or microturbine
- Stirling engine combined with a solar dish
- Wind turbines with battery storage and diesel backup generators
- Engines (and other prime movers) combined with energy storage devices such as flywheels

Hybrid power generation systems contain two or more power generation sources in order to balance each other's strengths and weaknesses. Hybrid systems are being developed to improve on the performance of an individual DG device. Energy storage devices such as flywheels are being combined with IC engines and microturbines to provide a reliable backup power supply [18]. The strengths and weaknesses of hybrid systems have been listed in Table 8.

Table 8 Strengths and weaknesses of hybrid systems

Hybrid Systems	
Strengths	**Weaknesses**
Increased fuel efficiency	High capital costs
Potential for lower maintenance costs, especially in remote applications (depending on the technology)	
Potential use of waste heat	

2.3.9 Combined Heat and Power

Combined heat and power (CHP) systems simply capture and utilize excess heat generated during the production of electric power. CHP systems offer economic, environmental and reliability-related advantages compared to power generation facilities that generate only electricity.

Table 9 Strengths and weaknesses of combined heat and power systems

Combined Heat and Power	
Strengths	**Weaknesses**
Better economics (reduced energy consumption, reduced energy costs)	Magnitude of the efficiency increase depends on the ratio of electric to thermal demand, the total energy utilization
Lower emissions (avoided energy consumption to generate heat)	May require additional design/integration during installation (for non-packaged systems)
Higher overall efficiency	Higher first cost, increased maintenance costs
Improved reliability	

Distributed power generation systems, which are frequently located near thermal loads, are particularly well suited for CHP applications. The thermal energy recovered from distributed generators is typically in the form of steam or hot water. The overall cost of CHP depends on the type of the technology used [15]. The strengths and weaknesses of combined heat and power systems have been listed in Table 9.

2.3.10 Small – scale hydro turbines

Small scale hydropower has been used for hundreds of years for manufacturing, including milling grain, sawing logs and manufacturing cloth. Small hydro plants may be connected to conventional electrical distribution networks as a source of low-cost renewable energy. Alternatively, small hydro projects may be built in isolated areas that would be uneconomic to serve from a network, or in areas where there is no national electrical distribution network. For small-scale hydro systems, the capital cost range from 900 to 1500 $/kW [20]. The strengths and weaknesses of small-scale hydropower plants have been listed in Table 10.

Table 10 Strengths and weaknesses of small-scale hydropower plants

Small-Scale Hydro Systems	
Strengths	**Weaknesses**
Efficient energy source	Suitable site characteristics required
Reliable electricity source	Energy expansion not possible
No reservoir required	Low-power in the summer months
No emission	

2.3.11 Other Renewable Sources

2.3.11.1 Biomass

Biomass consists of organic residues from plants and animals that are obtained primarily from harvesting and processing of agricultural and forestry crops. These are used as fuels in direct combustion power plants.

2.3.11.2 Geothermal

Geothermal energy is produced by the heat of the earth and is often associated with volcanic and seismically active regions. Hot water and, in some instances, steam can be used to make electricity in large power plants. Hot water can also be put to direct use, such as heating greenhouses or other buildings.

2.3.11.3 Solar Thermal

The intense energy of the sun has long been used to heat liquids. The sun's heat can be used in two ways with homes and businesses. The sun is used to heat water for domestic hot water systems, or the sun's light can be concentrated and water temperatures increased to make steam and electricity.

2.3.11.4 Wave Power

Wave power is the transport of energy by ocean surface waves, and the capture of that energy to do useful work — for example for electricity generation, water desalination, or the pumping of water (into reservoirs). Wave power is a renewable energy source. Wave power generation is not currently a widely employed commercial technology.

2.3.11.5 Tidal Power

Tidal power, sometimes called tidal energy, is a form of hydropower that converts the energy of tides into electricity or other useful forms of power. Although not yet widely used, tidal power has potential for future electricity generation. Tides are more predictable than wind energy and solar power. Tidal power is the only form of energy which derives directly from the relative motions of the Earth–Moon system, and to a lesser extent from the Earth–Sun system [21].

2.3.12 Evaluation of Distributed Generation Resources

Three factors are considered for the evaluation of distributed energy resources:

- The stability of the power source
- The ability to follow changes in load
- The reliability (availability) of the source.

On reciprocating engines, combustion turbines, and microturbines, the burn rate of the fuel/air mixture controls the power output. The real power output is controllable and responds to load changes fairly quickly. These combustion-based generators are normally very stable sources (unless the fuel supply is poor). Wind turbines and photovoltaics produce variable output that is normally not controllable. One of the main concerns of wind turbines on distribution circuits is the possibility of voltage flicker due to pulsating output, mainly because the tower shades the blades for part of their rotation. Sunshine variability also causes variation in solar-panel outputs, but the changes are normally slow enough to limit flicker problems. Neither of these can follow load. Fuel cells have load-following capability, but it is significantly slower than combustion generators. Fuel cells and photovoltaics have no natural provision to provide short-time overloads (some manufacturers include batteries or ultracapacitors to add this capability). This helps control fault currents but limits their ability to supply motor starting current and respond to loads. The availability and reliability of the energy source plays a role in some applications. Combustion engines and turbines are easily dispatchable. Photovoltaics and wind generation are non-dispatchable; the energy source is not always available. Small hydro units may or may not be dispatchable, depending on the water levels.

2.4 Distributed Generation Power Converters

The primary energy resource is converted to electrical energy via electric generators. Historically, most electric generators are rotating machines, synchronous or asynchronous. The generator has a stator, which is stationary, with a set of ac windings and a rotor, which is rotated by the prime mover, with windings of AC or DC. Power conversion is accomplished through the interaction of the magnetic fields of the stator and rotor circuits [22]. With the improvements in semi-conductor technology, the usage of static power converters has increased in electricity generation applications. Inverters convert power statically and are based on power semi-conductor devices, digital signal processing technologies, control and communication algorithms.

Three power converters convert the power output of the aforementioned DG resources to interface with standard 50 or 60-Hz systems:

- Synchronous Generator (SG)
- Asynchronous Generator
- Static Power Converters (converters, inverters)

Synchronous generators are used when the speed of the prime mover is relatively constant. All large central generators and most stand-alone schemes use SG for their high efficiency and independent control of real and reactive power. However, some DG plants having rotating systems with variable speed use AG and there is increasing use of power electronic interfaces. Asynchronous machines are widespread on the power system as asynchronous motors but are not widely used as generators, in spite of their apparent simplicity of construction and hence potential economy, because of the defined relationship between real power exported and reactive power drawn. AG has the significant benefit of providing large damping torques in the prime mover drive train. Also, inverters are used to connect distributed energy resources which produce DC and with prime movers which operates at variable speed [13].

Table 11 Power converters for different distributed energy resources

Distributed Energy Resources	**Synchronous Generator**	**Asynchronous Generator**	**Inverter**
Reciprocating Engines	✓		
Combustion Turbine	✓		
Microturbines			✓
Stirling Engines			✓
Fuel Cells			✓
Photovoltaic Cells			✓
Energy Storage Technologies			✓
Wind Turbines	✓	✓	✓
Combined Heat and Power	✓		✓
Small-Scale Hydro Power	✓		
Other Renewable Sources			✓

Normally, reciprocating engines, combustion turbines and hydro power turbines interface through SG. Microturbines, fuel cells, energy storage techniques, fuel cells, photovoltaics and many renewable resources interface through inverters. Wind turbines interface through AG or inverters, rarely through SG. In Table 11, the distributed energy resources and the interfaces used for them are listed [18].

2.4.1 Synchronous Generators

Most generators in service are SG. SGs are mainly utilized in grid interfacing of diesel and gas-fired engines and small hydro DG systems.

SG consists of an armature winding located on the stator which is connected to the three phases of the network and a field winding on the rotor which is fed from a dc source. The armature winding develops an mmf (magneto motive force) rotating at a speed proportional to the supply frequency. The field winding produces an mmf which is fixed with respect to the rotor. In normal operation the rotor, and so the field winding, rotates synchronously with the mmf developed by the stator with its relative angle, the load angle, determined by the torque applied to the shaft.

Most distributed SG uses a voltage-following control mode. This differs from large generators on the electric system, which have controls to regulate voltage (within the limits of the var capability). Distributed generators normally follow the utility voltage and inject a constant amount of real and reactive power (so the power factor stays constant). Normally, most DG operators run at unity power factor since that produces the most watts for a given kVA rating. Also, DG plants may wish to operate at a fixed power output, or fixed power exchange with the network, disregarding the network frequency.

The performance of the synchronous generator is strongly influenced by its excitation system particularly with respect to transient and dynamic stability, and the ability of the generator to deliver sustained fault current. Since the excitation current does not require an outside source, these generators could operate in stand-alone or grid-connected mode. Supply of sustained fault current is particularly important for DG due to their relatively small ratings and the long clearance times typically found in distribution systems. The ability of a small generator to provide adequate fault current for the quick operation of the time-delayed overcurrent protection requires careful attention during the design of DG scheme.

Synchronization is important when connecting SG. If a large machine is out of synch with the utility when it is connected, the sudden torque can damage the generator, and the connecting switch and other devices will have a large voltage disturbance. To avoid these problems, synchronizing relays are required for SG to ensure that the voltage, frequency, phase angle, and phasing are the same on the utility and generator. Normally, the generator is brought up to speed, and the field current is adjusted to bring the voltage close to the utility system. The frequency is more precisely adjusted to bring it within 0.5 Hz of the power system. Then, the synchronizing relay allows closing when the two voltages are within 10^{o}.

2.4.2 Asynchronous Generators

AG is used in a few DG applications, mainly in wind-turbine applications. AG is simpler than SG. It has several advantages, such as robustness and mechanical simplicity and, as it is produced in large series, it also has a low price. They do not have exciters, voltage regulators, governors or synchronizing equipment. The major disadvantage is that the stator needs a reactive magnetizing current. It has to receive its exciting current from another source and consumes reactive power. The reactive power may be supplied by the grid or by a power electronic system. The generator's magnetic field is established only if it is connected to the grid. The rotor of an AG can be designed as a so-called short-circuit rotor (squirrel cage rotor) or as a wound rotor. Wound rotor AG is used in special applications. Squirrel cage asynchronous machines are found in a variety of types of small generating units. The main reason for their use is the damping they provide for the drive train although additional benefits include simplicity and robustness of their construction and the lack of requirement of synchronizing.

Although the simple wound rotor AG is rarely used, with the doubly-fed concept, the usage of this type of generators has increased. In doubly-fed AG, a variable-speed operation over a large but restricted range is allowed. Both during normal operation and faults the behavior of the generator is thus governed by the power converter and its controllers.

2.4.3 Inverters

Many types of small generators best interface with utility and utilization power through an inverter. Unlike large generators, which are almost exclusively 50/60 Hz synchronous machines, DG include variable frequency sources such as wind energy, high frequency sources such as micro-turbine generators, and direct energy conversion sources producing dc voltages such as fuel cells and photovoltaic [23]. In large wind parks, a common DC busbar collects the power supplied from each turbine through converters and delivers it to the utility grid via one inverter and one transformer [24]. An electric power converter provides an interface between a non-synchronous source of power and the grid so that the two may be properly interconnected.

For the case of inverters, the input voltage to the inverter is generally a non-regulated DC voltage. The output voltage is at the frequency and magnitude of the utility. When converters are used, the input of the converter does not meet the utility requirements for frequency and voltage magnitude. Output of the converter is regulated voltage. In this case, whether the regulated voltage is passed into an inverter or DC power is used in a DC system.

Static power converters are based on diodes, transistors and thyristors and have ratings compatible with the grid applications. Some types require the grid to operate; some may continue to operate after a utility failure. An advantage of power electronic converters is their controllability. Anyway, a converter has to be equipped with a controller that can be used to achieve a number of functionalities. Voltage or reactive power control could be integrated in converters as an additional feature [25]. Also, static power converters technology could be used with protective relays and communication options. However, considering the protection issues, semiconductor devices are almost not overloadable [26].

2.5 New Power System Scheme under the Scope of Turkish Renewable Targets

In Turkey, renewable energy resources have started growing in importance in the last decade. In June 2008, Turkish Secretariat General of the National Security Council (*Milli Güvenlik Kurulu-MGK*) has advised to increase the usage of renewable energy resources as much as possible due to the fact that Turkey has to decrease the dependency of foreign energy resources such as natural gas and petroleum for an independent foreign policy. This advice shows that the incentives and credits for investments of renewable resources will increase in coming years. Also, both European Union and World Band are encouraging renewable energy projects in Turkey by supplying credits in good conditions. Turkish renewable target is to generate electricity by renewable resources with domestic industrial contribution as much as possible. Moreover, people are willing to construct small generation units for supplying their needs and selling the extra energy to the grid.

These events show that in coming years, the penetration level of DG of both renewable and non-renewable resources into the power system will increase sharply. This penetration will be through the distribution system level since the connection of such distributed facilities to the grid at transmission level will be uneconomical. The centralized power system structure has begun to change towards a decentralized power system in which active distribution systems exist.

In this scheme, DG facilities will be located near loads as much as possible. The presence and operation of the transmission system is still very important, but the amount of power of DG facilities will catch the supply of centralized generation.

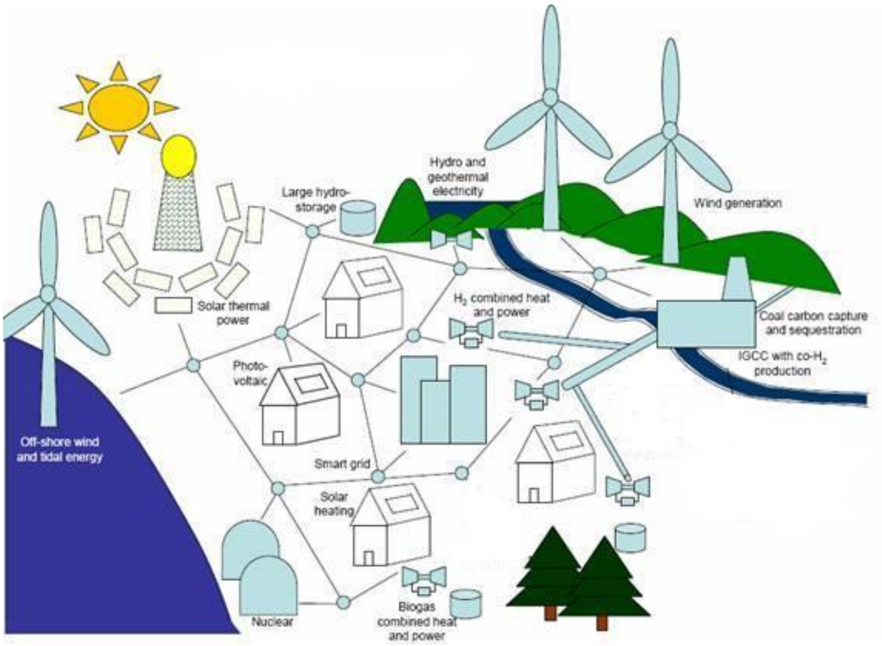

Figure 5 Future power system with DG [27]

As can be seen in Figure 5, there are lots of energy resources such as wind, photovoltaic, micro generation units connected to the grid. As the penetration of DG facilities gets larger, a dispatch center at each distribution region for DG will be needed. Therefore, well-designed control and monitoring systems should be located in DG facilities. Also, the distribution authority should prepare a requirements list for different types of DG facilities. The protection, control and monitoring requirements should be determined, as well.

CHAPTER 3

TECHNICAL AND OPERATIONAL IMPACTS OF DISTRIBUTED GENERATION

3.1 Introduction

DG is small electricity generation from different resources generally connected to the utility at distribution level. With the new trend of renewable energy generation, DG has become popular for a decade. Since the amount of investment to be done is much smaller and could be afforded by even small companies, the interest on DG has increased in Turkey.

The distributed generators, whose resources are renewable, are mostly connected to utility at distribution systems of rural areas. The presence of DG in these areas could cause steady-state voltage problems, protection problems with increased short-circuit currents and power quality problems. Before permitting the connection of distributed generators to the utility, some criterion should be considered to maintain the quality of supply in distribution systems in presence of distributed generators.

In the sections given below, firstly, candidate distributed generators will be selected for obtaining minimum line loss. This is done, because there are no potential generator options with a specific power rating at this level of the study. There are different types of generators which are used for DG purposes like SG with pf or voltage control mode for reactive power control, AG with or without power factor correction systems and static generators which use inverters as the utility interface. Later, the analyses will be conducted for the distribution system with DG considering the criterion listed below:

a. Line Loading: The presence of distributed generators should be taken into consideration from the line loading point. The medium-voltage (MV) lines could be overloaded and need refurbishment after the installation of distributed generators or the presence of distributed generators could relieve the loading of the line and deferral the line investment, which is a positive impact on the system.
b. Steady-State Voltage Variation: The distribution system has a limit of ±10% steady-state voltage variation limit for the total variation in both MV and low-voltage (LV) levels. Half of this variation limit is valid for MV level. The presence of distributed generators could cause the voltage profile along the line to exceed or drop below the limits. Therefore, the steady-state voltage variation should be considered in presence of DG.
c. Short-Circuit Current Contribution: Short-circuit capacity, that is, the maximum amount of short-circuit current to be never exceeded is an important concern for the design of distribution systems. The amount of fault current determines the rating of the switchgear and the thermal and mechanical features of the equipments used. When distributed generators are connected to the utility at the distribution level, the short-circuit capacity of the network changes. This change could lead to installing new protection devices or the adjustment of the relay settings. So, it is necessary to investigate the contribution of the distributed generators to the short-circuit current or capacity of the distribution system.
d. Voltage Sags-Swells: In distribution systems, unbalanced faults like single line-to-ground (L-G) faults are seen frequently. Voltage sags or swells could be observed during these types of faults. The occurrence of voltage sags and swells has negative impact on power quality. The presence of distributed generators could severe the voltage sag and swell problem. Because of this

possibility, the voltage sag and swell should be taken into consideration in presence of distributed generators.

e. Transient Stability: Distributed generators, depending on the technology used, have very low inertia and short time constants. These types of generators could lose their synchronism or stability easily because of a fault in the power system. The analyses of transient stability of distributed generators will result with a critical clearing time which is the maximum time for clearance of a fault before a generator loses its stability. This critical clearance time could be taken into account during the design of the protection of the system.

f. Voltage Stability: The reactive power support of the network and distributed generators affect the voltage stability primarily. The level a bus could draw active power depends on the reactive power support to that bus. The evaluation of how close is the bus to the voltage instability is a measure of voltage security and could be evaluated by system operators to prevent voltage instability [28]. Therefore, the effect of DG on the voltage stability could be investigated.

Distribution systems' design differs according to the regional and operational concerns. It is very common to find different distribution network topologies with different voltage levels, equipments and protection schemes, even in the same province. Also, it is very difficult to obtain the system data of a specific area from the system operators. The liveliness of the distribution system, that is, the frequent change of the system by addition of new loads, feeders, etc makes the data less reliable. Due to these reasons, it is convenient to conduct the analyses on a sample distribution system.

The sample distribution system can be seen in Figure 6. The external grid is the 154 kV-grid with X/R ratio of 10. The distribution network is fed from the external grid through 50 MVA HV/MV network transformers. The maximum demand is 3.44 MVA and the loads are not uniformly distributed.

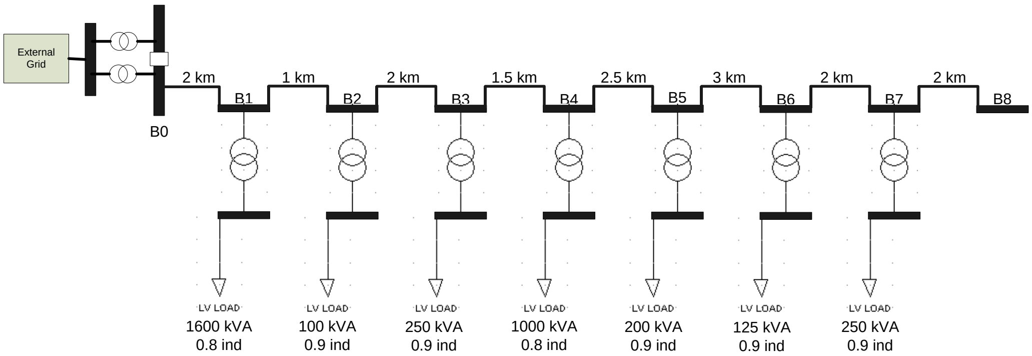

Figure 6 Sample distribution system

Table 12 Network and equipment data

Component Name	**Data**
External Grid	Un=154 kV S_k"max=1500 MVA X/R=10
HV/MV Network Transformers	S = 50 MVA u_k = 12.5% P_{kr} = 160 kW t = 154/34.5 kV
General Data for Lines	1/0 ACSR overhead line R_l = 0.6468 Ω/km X_l = 0.4906 Ω/km U_n = 34.5 kV I_n = 100 A
Line B0-B1	l = 2 km
Line B1-B2	l = 1 km
Line B2-B3	l = 2 km
Line B3-B4	l =1.5 km
Line B4-B5	l = 2.5 km
Line B5-B6	l = 3 km
Line B6-B7	l = 2 km
Line B7-B8	l = 2 km
General Data for Distribution Transformer	t = 34.5 / 0.4 kV
Distribution Transformer-B1	S = 1600 kVA u_k = 6% P_{kr} =16 kW
Distribution Transformer-B2	S = 100 kVA u_k = 4% P_{kr} =1 kW
Distribution Transformer-B3	S = 250 kVA u_k = 4% P_{kr} =3 kW
Distribution Transformer-B4	S = 1000 kVA u_k = 6% P_{kr} =10 kW
Distribution Transformer-B5	S = 200 kVA u_k = 4% P_{kr} =2 kW
Distribution Transformer-B6	S = 125 kVA u_k = 4% P_{kr} =1 kW
Distribution Transformer-B7	S = 250 kVA u_k = 4% P_{kr} =3 kW
Load B1	S_l = 1600 kVA pf= 0.8 ind
Load B2	S_l = 100 kVA pf= 0.9 ind
Load B3	S_l = 250 kVA pf= 0.9 ind
Load B4	S_l = 1000 kVA pf= 0.8 ind
Load B5	S_l = 200 kVA pf= 0.9 ind
Load B6	S_l = 125 kVA pf= 0.9 ind
Load B7	S_l = 250 kVA pf= 0.9 ind

Small loads are distributed kilometers away from each other and some larger loads like plants are located between these small loads. The data of the network and equipment is listed in Table 12.

DigSilent, PowerFactory, which is a commercial digital simulation and network calculation software, has been used as the simulation tool for analyzing the criterion above on the sample distribution system. This program is capable of calculations of load flow and short-circuit, stability functions and so on. The relevant power system elements for the analyses are present in the element editor of the software. After the elements are located in the single line diagram, project types of each element should be defined to continue with simulations. Using the data of the network and equipment listed above, the types of each element have been defined. Also, for the distributed generators to be used in simulations, project types of each generator have been defined in the program. The relevant data of the distributed generators are listed in Table 13. At the beginning of the analyses, 1000 kVA-distributed generators have been used.

Table 13 Data of the generators

Sample Synchronous Generator	
Generator	Synchronous S_G = 1000 kVA U_n = 400 V x_d'' = 0.18 pu $\cos\varphi$ = 0.9 lag.
Transformer	S_T = 1250 kVA u_k = 6% t = 34.5/0.4 kV
Sample Asynchronous Generator	
Generator	Asynchronous S_G = 1000 kVA U_n = 400 V I_{lr}/I_n = 8 pu
Transformer	S_T = 1250 kVA u_k = 6% t = 34.5/0.4 kV
Sample Static Generator	
Generator	Synchronous with inverter S_G = 1000 kVA U_n = 400 pf = 1 MVA_{SC}= 2000 kVA
Transformer	S_T = 1250 kVA u_k = 6% t = 34.5/0.4 kV

In coming parts of the studies, the selection of convenient distributed generators for different buses with the aim of achieving minimum line loss will be done using the system elements explained above. Also, analyses on the criterion above will be conducted using this sample circuit.

3.2 Line losses

In a radial distribution system, the whole load is supplied with power flowing from the substation transformer to the loads via feeders or underground cables. This unidirectional power flow causes high currents, thus high losses, especially in the substation transformer and the first segment of the feeder. The losses gradually decrease towards the distant load as the current passing through the feeder decreases.

With the addition of DG, the whole load in the feeder is fed from the power not only coming from substation transformer but also supplied by the distributed generators. The location, output power and the presence of reactive power control of the distributed generators affect the line losses along the feeder. The location and the output power of the distributed generator determine the loads to be fed from the generator instead of the utility. Also, with the feature of the reactive power control, the reactive power support is maintained by the generator. This power factor compensating effect makes the line losses decrease.

In the following analyses, the convenient location for minimum line loss will be investigated. For this purpose, different generator types with different features, such as AG with and without power factor correction system and SG with pf or voltage control mode for reactive power and generating units with inverter interface, have been used in DigSilent PowerFactory program. In this step, all generators have output power of 1000 kVA and will be connected to utility at each bus as shown in Figure 7.

After the convenient location has been found for different generator options, the optimum output power will be chosen considering the minimum line loss.

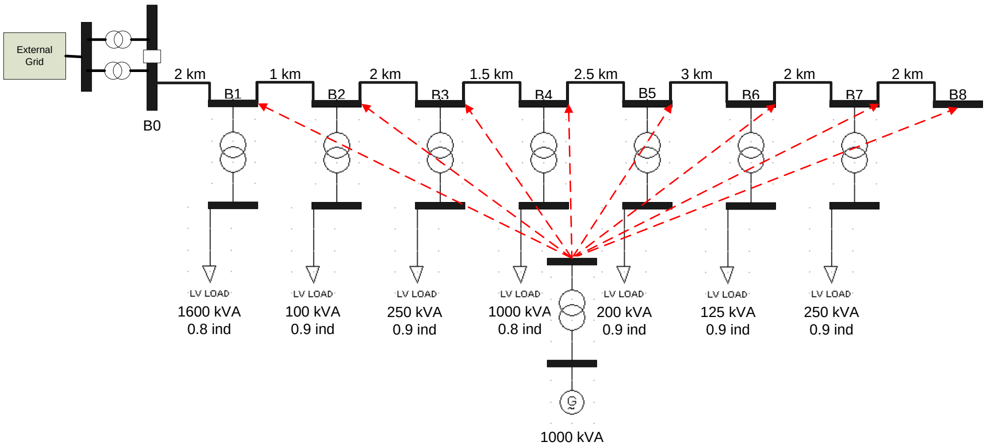

Figure 7 Connection of DG to the utility

The analysis starts with finding minimum loss location for an AG of 1000 kVA output power. In the first case, there is no power factor correction (PFC) for AG. In the second case, PFC is assumed to be used with the asynchronous machine. 1/3 of the reactive power need of the generator has been supplied by local power factor correction systems, which is usual for compensation [13]. Line losses on the feeder are calculated for both compensation cases of one asynchronous machine at one bus for each step. Thus, eight loss values with AG (B1-B8) and one value without AG (B0) are found.

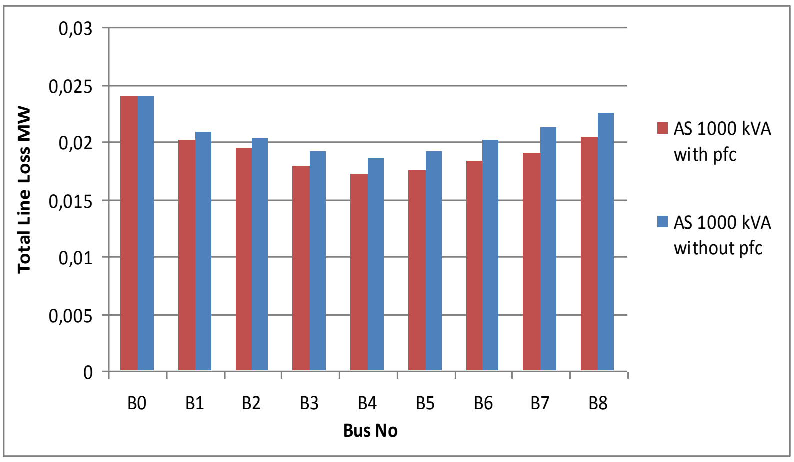

Figure 8 Total line loss values for a 1000 kVA AG penetration at different buses

As seen in the Figure 8, the minimum loss values for both cases are seen at Bus4. The total line loss for AG at B4 with PFC is 0.0172 MW. A total line loss of 0.0186 MW is found for the case of AG without PFC connected at Bus4. In the second step of the analysis, different output values of AG are connected at Bus4 to find the optimum output power for minimizing the losses in the feeder.

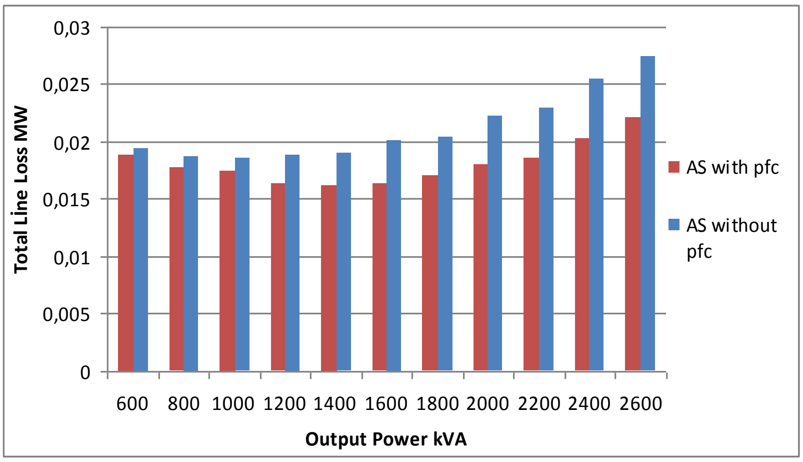

Figure 9 Total line loss values for different AG penetration at Bus 4

In Figure 9 below, it is seen that for AG at B4 with PFC case, 1400 kVA gives the minimum line loss. However, for AG at B4 without PFC case, 1000 kVA gives the minimum line loss. These results have been found after the analysis with 600-2600 kVA asynchronous machines. As seen in the figure, the shape of the whole graph turns into a U-shape, and this means that it is not necessary to try with higher values than 2600 kVA.

The results have shown that the presence of reactive power compensation of 1/3 of the need of AG has increased the convenient output power level of AG connected at B4 by 4/10.

It is also possible to utilize SG as distributed generators. SG has the advantage of reactive power control by the control of the excitation current flowing through the rotor winding. There are two reactive power control mode for SG. First is the power factor control mode by which the predetermined active and reactive power is supplied by the generator. The second is the voltage control mode in which the reactive power supply of the generator is determined by the target terminal voltage.

With SG, three analyses have been conducted. In the first analysis, a SG of 1000 kVA with unity power factor has been connected to the buses from B0 to B8 and the total line loss for each connection location have been written. Then, the same method has been used for SG with pf=0.9 capacitive and inductive. As seen in Figure 10, the minimum loss has been recorded for the connection of 1000 kVA SG with pf=0.9 inductive to the B5. The option with power factor control mode of pf=0.9 ind has 30 % less line loss than the option with unity pf for the connection at Bus5. That the reactive power control mode with capacitive power factor made the line losses worse is also seen in the same figure.

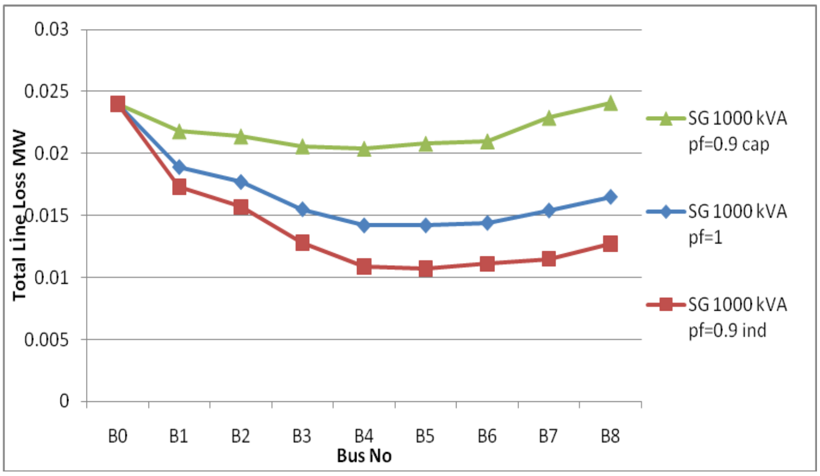

Figure 10 Total line loss values for a 1000 kVA SG with pf control mode penetration at different buses

In the next step, as done for AG, the different output power levels for SG connected at Bus 5 with reactive power control mode of pf=0.9 inductive will be investigated.

The presence of reactive power support has shifted the optimum output power level of the generator to 1800 kVA for the connection at Bus 5. The other power levels and their corresponding line loss values could be visualized in Figure 11.

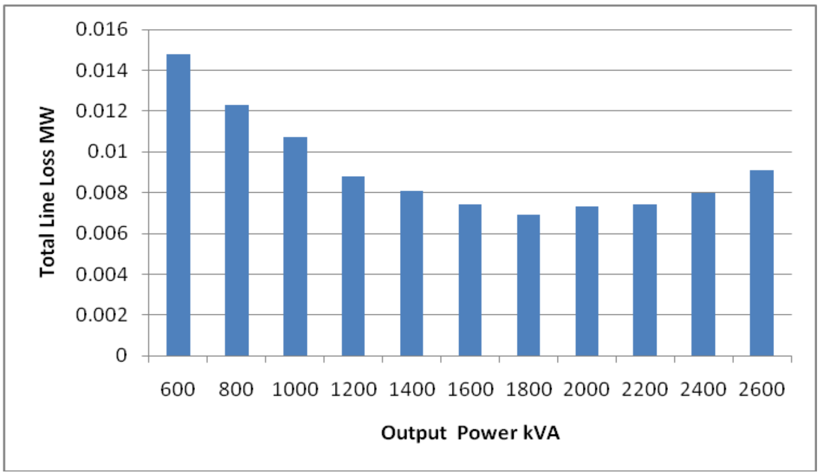

Figure 11 Total line loss values for different SG with pf control mode penetration at Bus 5

It is also possible to choose the reactive control mode of SG as constant voltage mode. In the following analysis, the total line loss of a 1000 kVA SG with constant voltage control connected to different buses is investigated. The constant voltage mode of the reactive power control is adjusted to 1 pu.

As seen in the Figure 12, the most convenient bus for the connection of a SG with constant voltage control mode concerning the total line losses is the Bus 5 like the above analyses.

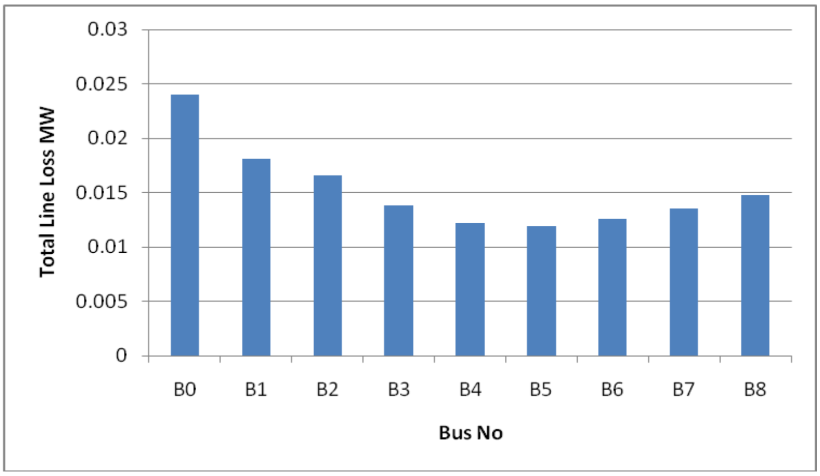

Figure 12 Total line loss values for a 1000 kVA SG with constant voltage control mode penetration at different buses

As the second step, different output power levels have been investigated concerning the total line losses. The output of SG changes from 600 kVA to 2600 kVA. As seen in the Figure 13, the most convenient output power is 1200 kVA for SG with constant voltage reactive power control mode.

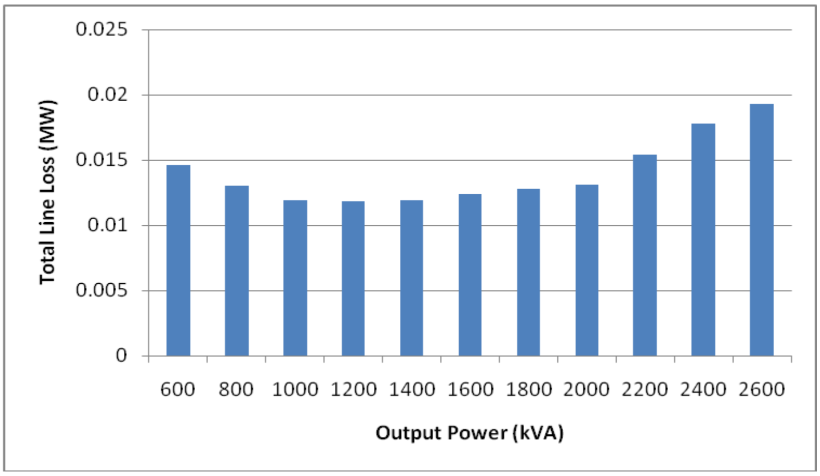

Figure 13 Total line loss values for different SG with constant voltage control mode penetration at Bus 5

During these analyses, the line loading should also be considered. Due to the output power of a generator which is suitable for line loss minimization, the maximum current carrying capacity of the distribution lines could be exceeded.

Some distributed energy resources like some wind power applications, photovoltaic, fuel cell, etc. are connected to the network with inverters. This type of generator combination is called static generator. With this type of power converters, the reactive power control is also possible but the pf of the static generator has been adjusted to unity. As similar to previous steps, first a 1000 kVA generator is connected to each bus one-by-one. Then, the most convenient output power of the generator connected to the most suitable bus is determined for minimum loss.

In Figure 14, the most convenient bus is found to be Bus 5 with a line loss of 0.0138 MW. In Figure 15, the most convenient output power for the static generator connected to Bus 5 is found to be 1400 kVA. The line loss for this configuration is 0.013 MW.

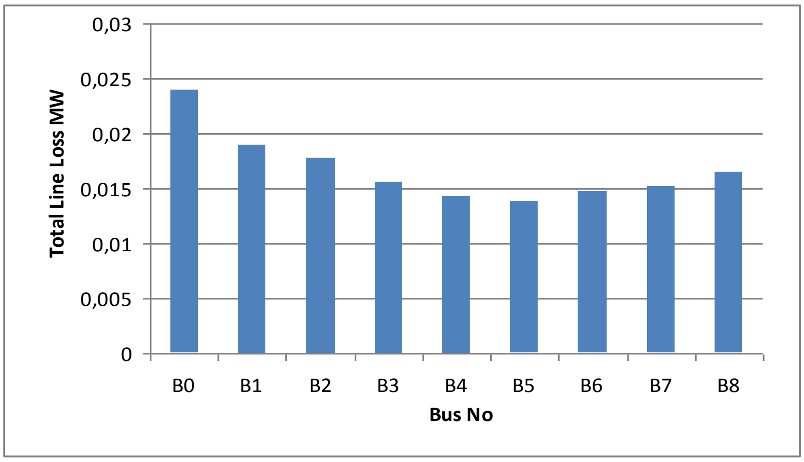

Figure 14 Total line loss values for a 1000 kVA static generator penetration at different buses

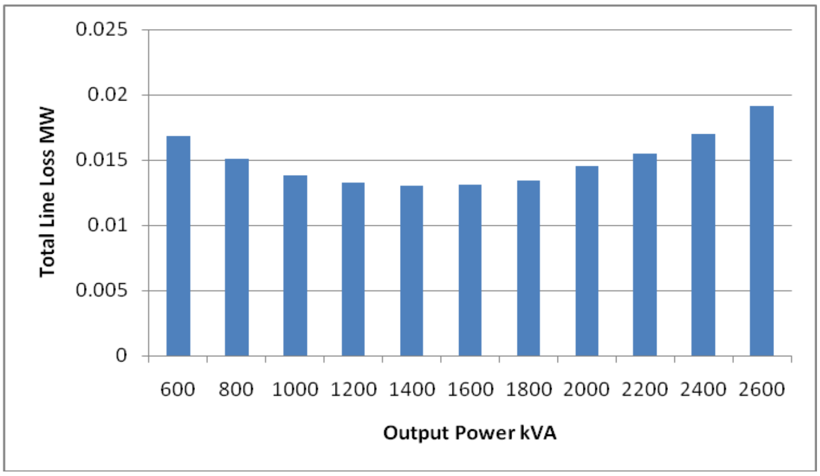

Figure 15 Total line loss values for different static generator penetration at Bus 5

After the analyses, the suitable options for the type and location of the distributed generators have been tabulated in Table 14.

Table 14 Types of the selected distributed generators, power ratings and connection buses

Type of the Distributed Generator	**Output Power (kVA)**	**Connection at #Bus**
Asynchronous Generator with Power Factor Correction	1400 kVA	Bus 4
Asynchronous Generator without Power Factor Correction	1000 kVA	Bus 4
Synchronous Generator with Constant pf Reactive Control Mode	1800 kVA at pf=0.9 ind	Bus 5
Synchronous Generator with Constant Voltage Reactive Control Mode	1200 kVA	Bus 5
Static Generator	1400 kVA	Bus 5

In the results, it is seen that with the addition of DG in small amounts, the losses start to decrease. As the penetration level is increased, the losses are minimum and after a critical penetration level, the line losses start to increase.

In order to make a comparison between the generator options considering the total line losses, among the 1000 kVA generators connected to Bus 5, the minimum line loss has been obtained for the pf reactive control mode SG operated at 0.9 inductive power factor. AG with power factor correction system has less line loss than AG without power factor correction system. These comparisons show that reactive power supply of the generator leads to less line loss since the local reactive supply decreases the amount of current flowing through the feeders.

Normally, most distributed generator operators run at unity power factor since that produces the most watts for a given kVA rating. Since the distribution companies have to guarantee the quality of the supplied power, it is possible for a distribution company to choose operating SG with a power factor different than unity.

The total maximum load along the feeder is 3435 kVA and the total length of the feeder is 14 km. In most of the analyses, the convenient bus for minimum line loss is Bus 5 and Bus 5 is at the 9^{th} km of the feeder. Also, the most convenient output power for minimum line loss is between 1000-1800 kVA. A general result could be obtained by considering the output power and the location of connection for the ideal displacement of the distributed generator using the total load along the feeder and the length of the feeder. As a result, it could be said that a distributed generator connected at the 2/3 of the feeder length with an output power of 0.3-0.6 of the total load on the feeder gives the minimum line loss.

3.3 Line loading

The presence of distributed generators could overload the medium voltage lines, thus, could cause extra investment for the installation of distributed generators. On the contrary, installation of these generators could reduce the line loadings, thus, defer the future investments for the 154/36 kV substation and MV level equipment, which will be needed in no DG case. This could be understood by investigating the line loading values for different generator options which are listed in Table 14 for minimum line loss.

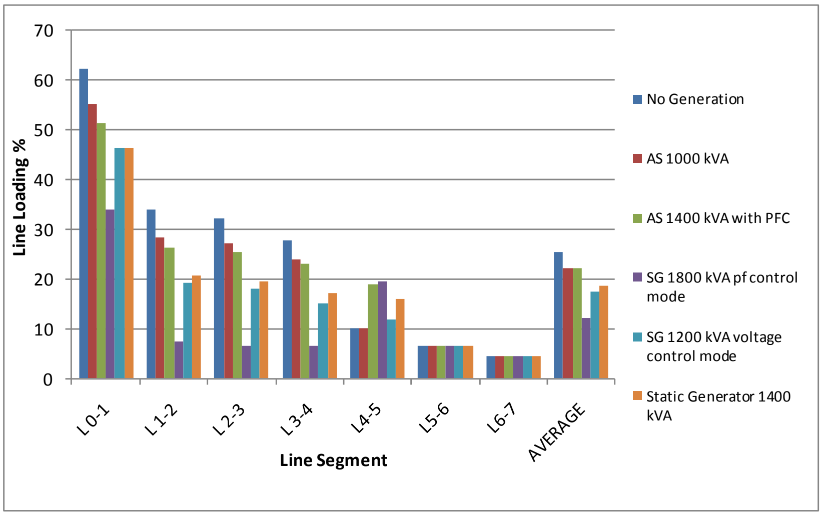

Figure 16 Percentage loading of MV lines for different cases

As seen in Figure 16 above, for the no DG case, the average line loading is about 25%. For SG with pf control mode of set to 0.9 inductive generator option decreases the overall line loading to 12.07%, about half of the no DG case. When the line between 154/36 kV substation and the first bus, B1, is considered, the loading of this line drops to 34% from 62.17% for the same distribution generator option. These analyses show that in addition to less line losses, utilizing distributed generators in distribution system has positive impact on the line loadings and this leads to investment deferrals for distribution system equipments.

3.4 Steady State Voltage Profile

In a distribution system, for quality of power supply, it is necessary to limit the voltage variations within predefined limits against different loading schemes. In this part of the study, the voltage variation in a distribution system with the presence of DG will be investigated. The total allowable voltage variation in a distribution system is ±10%, which consists of ±5% in the low voltage part and ±5% for the medium voltage part of the distribution system [31]. Therefore, in the analyses given below, the limiting factor for the penetration of DG is ±5 % variation of the voltage profile along the lines.

Before installing or allowing installation of distributed generators, the utility engineers should analyze the worst operating conditions including

- no generation and maximum demand
- maximum generation and maximum demand
- maximum generation and minimum demand, which is 10 % of the maximum demand

so that the presence of distributed generators does not affect the allowable voltage profile [29] [30].

The steady-state voltage profile along MV lines for maximum and minimum demand and different generator options could be visualized in Figure 17 and Figure 18.

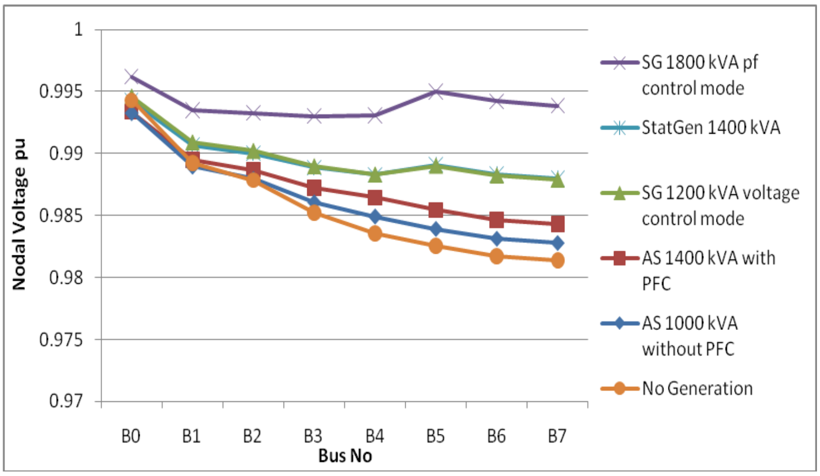

Figure 17 Steady-state voltage profile for maximum demand

In Figure 17 and Figure 18, it is seen that for the no generation case, the voltage variation is about 0.02 % for minimum demand and 2 % for maximum demand. For maximum demand case, the worst impact is seen for 1000 kVA-AG without PFC generator option but it still improves the steady-state voltage profile comparing with the no generation case.

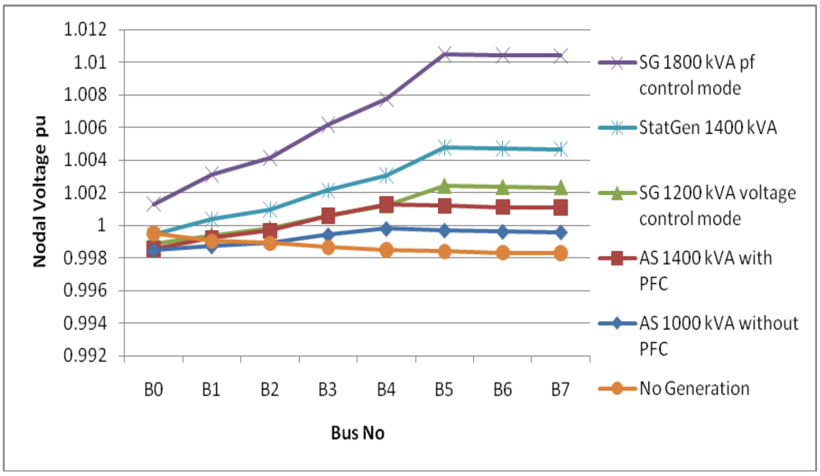

Figure 18 Steady-state voltage profile for minimum demand

Since there is no PFC with AG connected at Bus 4, the reactive power need of the generator is supplied by the network. This makes the voltage at Bus 4 decrease. For minimum demand case, the 1800 kVA-SG with pf control mode, the voltage rises over 1.01 pu, which very close to 1 pu. In SG with pf control mode, the reactive power to be supplied to the network is adjusted by a determined pf value given by the operator. Therefore, disregarding the level of the demand, SG continues to supply a constant reactive power to the network. This makes the nodal voltage rise at Bus 5.

Table 15 Generator terminal voltages in pu

Generator Type	**Output Power (kVA)**	**Minimum Demand**	**Maximum Demand**
AG without PFC	1000	0.9714	0.9861
AG with PFC	1400	0.9814	0.9961
SG pf control mode	1800	1.0261	1.0416
SG voltage control mode	1200	1	1
StatGen	1400	0.9965	1.0121

In Table 15, the terminal voltages for the different generator options have been listed. Related with its reactive power capacity, the generators are usually operated such that their terminal voltage does not exceed the nominal terminal voltage by ±0.05 pu. Only the terminal voltage of the 1800 kVA-SG with pf control mode is closer to the upper limit. The terminal voltage of SG with voltage control mode is 1 pu in both demand cases, as expected.

Two different cases could be analyzed for the voltage variation along the feeder. One is the steady-state voltage regulation of the distribution network which could be defined as the avearge voltage change along the feeder for maximum and minimum demand cases. During load variations, the voltage regulation should be as small as possible for the quality of supply. The second case is the change in the steady-state voltage profile against the disconnection of distributed generators during maximum and minimum demand. With this analysis, the load is held constant but the effect of sudden disconnection of the distributed generator is considered.

Table 16 Voltage regulation

Generator Type	**Voltage Regulation %**
AG without PFC	1.2908
AG with PFC	1.2883
SG pf control mode	1.2703
SG voltage control mode	1.1099
StatGen	1.2826
No generation	1.2971

In Table 16, the steady-state voltage regulation of the network with different generator options have been listed. It is seen that the presence of all types of generators has improved the voltage regulation when compared to the no generation case. SG with voltage control mode has the best improving effect since this type of operation adjusts the reactive power control concerning the terminal voltage of the generator.

The second analysis related with the steady-state voltage profile is to determine the voltage changes in the nodes when the distributed generators are suddenly disconnected. Some types of distributed generators like photovoltaics, wind turbines could suddenly disconnect from the network due to meteorological conditions or due to internal faults, the protection system of the generating unit could disconnect the unit from the network suddenly. These events could harm the quality of power supply and therefore, the effect of disconnection should be as small as possible. With this analysis, the effect of the sudden disconnection of different generators is evaluated for maximum and minimum demand cases.

Table 17 Voltage variation for disconnection

Generator Type	Maximum Demand %	Minimum Demand %
AG without PFC	0.096	0.092
AG with PFC	0.196	0.188
SG pf control mode	0.829	0.802
SG voltage control mode	0.404	0.233
StatGen	0.397	0.384

Considering the results in Table 17, SG with pf control mode has the worst effect on the voltage when disconnected. Since SG with pf control mode supply constant amount of reactive power, the voltage rises in normal operation. This rise causes a relatively great variation when SG with pf control mode is disconnected.

The analyses conducted for the cases related with steady-state voltage profile have shown that the selected generators do not violate the steady-state voltage limits. So there is no need to revise the selection of generators. Moreover, considering the variation for both maximum and minimum demand case and the disconnection case, the variations caused by the presence of the generators are very small and could be neglected for quality of supply point.

3.5 Short-Circuit Current

DG resources are connected to the utility at MV or LV distribution systems. These systems are planned as passive networks, carrying power from the transmission level downstream to the end-users uni-directionally. Therefore, the protection system design in MV and LV distribution networks is determined by a passive paradigm, i.e. no generation is expected in the network [25]. However, the presence of distributed generators in the distribution network contributes to the total fault level of the network. The total fault level is determined by the contribution of both the upstream grid and the distributed generator connected to the utility. Due to the contribution of distributed generators to the short-circuit currents, the protection or networks devices need to be updated or the settings of the relays used need to be readjusted to detect and clear the faults properly. Because of this reason, the short-circuit contribution of the distributed generator could be a limiting factor for the penetration level of DG [26].

Therefore, in this part of the study, the problem of increased short circuit currents due to distributed generators installed in distribution networks will be illustrated. The predetermined distributed generator options will be analyzed whether or not the short-circuit currents supplied by these generators exceed the setting values adjusted for uni-directional power flow in the distribution system. By electromagnetic transient simulations, the short-circuit current from each generator during balanced and unbalanced faults will be determined. The fault and ground resistances are set to 0.001 ohm [32].

In the previous analyses, the selected distributed generators selected for minimum line loss have been investigated for the steady-state voltage profile. None of the selected generators were eliminated due to the violence of the steady-state voltage limits.

This section of the study consists of two different cases. In the first case, different types of faults including three-phase (3P), line-to-line (L-L), L-G and line-line-ground (L-L-G) have been analyzed for the predetermined generator options. The position of the fault is the bus by which the generator is connected to the distribution system. That is, the aforementioned faults occur at Bus 4 for AG with/without power factor correction, at Bus 5 for the static generator and SG of pf and voltage control mode. In the second part, the fault contribution of each generator will be investigated for different types of the faults mentioned above at a different bus. Sample distribution system on which these studies are connected could be found in Figure 6.

The first generator option is the 1000 kVA AG. It was connected to the network at Bus 4. The fault current contribution of each phase of AG is listed in Table 18.

Table 18 The fault current contribution of AG in kA

Asynchronous Generator without PFC			
	Phase A	Phase B	Phase C
3P	8.69	8.69	8.69
L-G	1.29	0.62	0.62
L-L	0	7.53	7.53
L-L-G	0.36	7.54	7.51

As mentioned earlier, the usage of PFC systems is very common. 1/3 of the reactive power need of AG fault is supplied by PFC systems. Since the reactive power supply leads to the reduction in line losses, the power rating of this generator has been determined as 1400 kVA. The fault current contribution of AG with PFC is listed in Table 19 phase by phase. It is seen that the fault level of AG with PFC is greater than of the generator without PFC. This could be explained with the power rating difference between the two generators.

Table 19 The fault current contribution of AG with PFC in kA

Asynchronous Generator with PFC			
	Phase A	Phase B	Phase C
3P	12.67	12.67	12.67
L-G	1.87	0.94	0.94
L-L	0	10.97	10.97
L-L-G	0.53	10.99	10.95

The following generator options are connected to the network at Bus 5. Different types of faults now occur at Bus 5. The fault contribution of SG is listed in Table 20 and Table 21. The difference is that the former has a reactive power control of pf control mode. The latter has the voltage control as the reactive power control mode. Comparing the two SGs, it is seen that the pf controlled one has higher peak short-circuit value than the voltage controlled one. This is due to the pre-fault terminal voltage values of these machines which have been listed in Table 23 and the power rating of the machines.

Table 20 Phase fault currents of SG with pf control mode in kA

Synchronous Generator pf Control Mode			
	Phase A	Phase B	Phase C
3P	12.6	12.6	12.6
L-G	20.41	15.12	14.83
L-L	0.76	10.87	10.21
L-L-G	9.33	15.29	16.06

Table 21 Phase fault currents of SG with voltage control mode in kA

Synchronous Generator Voltage Control Mode			
	Phase A	Phase B	Phase C
3P	6.77	6.77	6.77
L-G	11.04	8.73	8.58
L-L	0.45	5.84	5.45
L-L-G	5.11	8.12	8.56

The static generator has a power rating of 1400 kVA. In Table 22, the fault currents of each phase of the static generator are listed. In the EMT simulations, only for the 3P short circuit case, the fault contribution of the static generator is displayed. The other fault types lead the static generator to no fault current contribution.

Table 22 The fault currents of static generator in kA

Static Generator			
	Phase A	Phase B	Phase C
3P	5.79	5.79	5.79
L-G	0	0	0
L-L	0	0	0
L-L-G	0	0	0

The figures below show the dynamic behavior of the two types of generator considering their stator currents. As done earlier, 3P and L-G faults have been simulated at the buses where the generators are connected. For the L-G fault, the fault occurs between Phase A and the ground. SG and AG have been simulated for 3P and L-G faults. AG's dynamic response against 3P and L-G faults could be seen in Figure 19 and Figure 20. The two alternative reactive power control mode of SG could be seen in Figure 21 and Figure 22 for 3P fault and Figure 23 and Figure 24 for L-G fault.

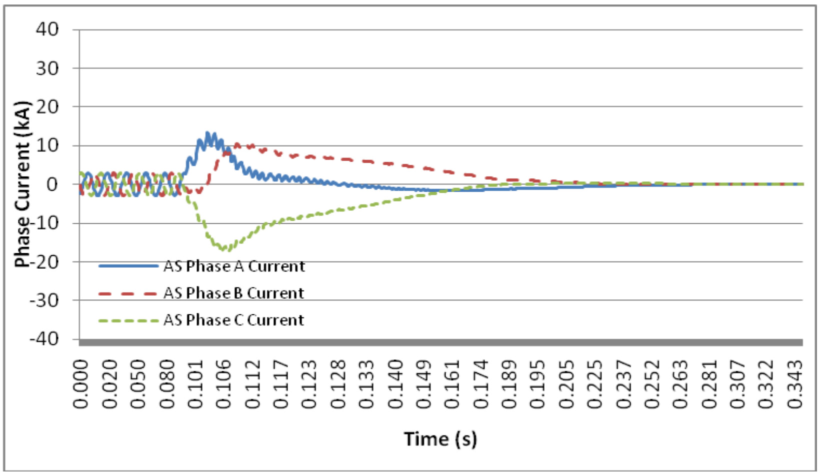

Figure 19AG's dynamic behavior against 3P fault at Bus 4

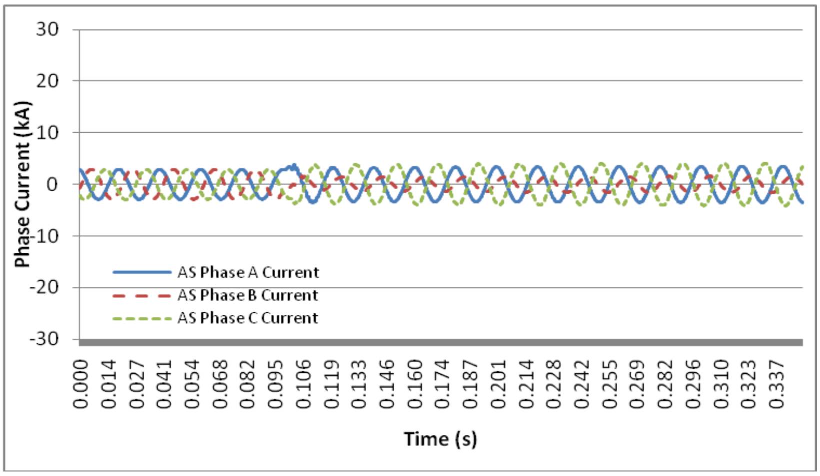

Figure 20 AG's dynamic behavior against L-G fault at Bus 4

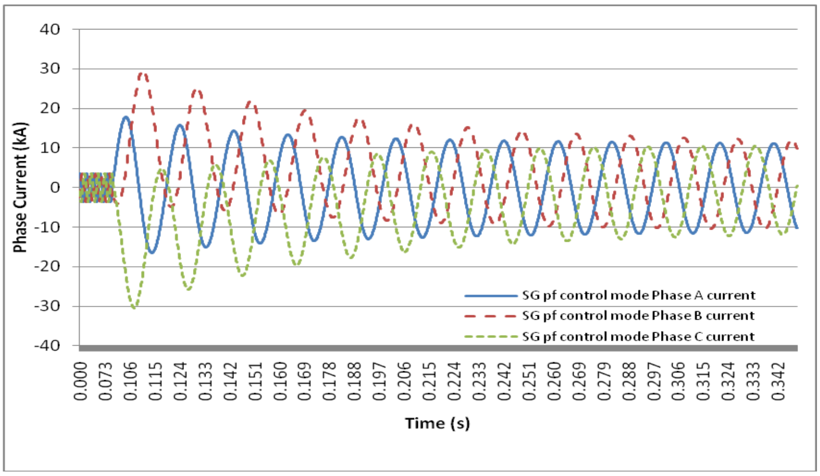

Figure 21 pf control mode - SG's dynamic behavior against 3P fault at Bus 5

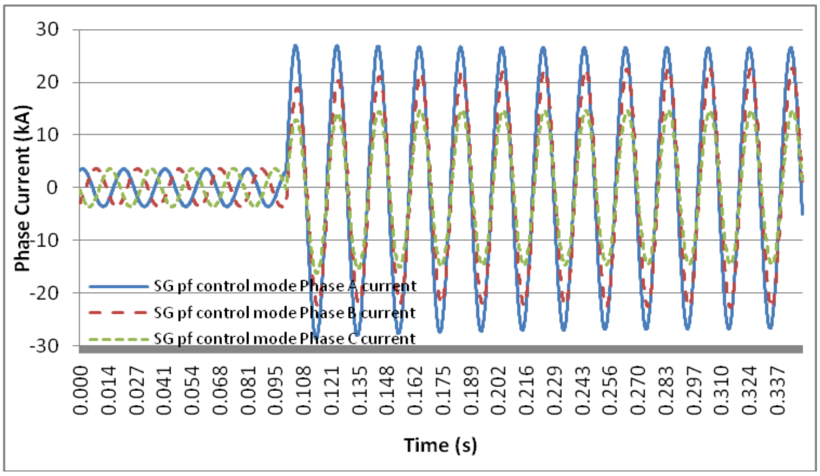

Figure 22 pf control mode - SG's dynamic behavior against L-G fault at Bus 5

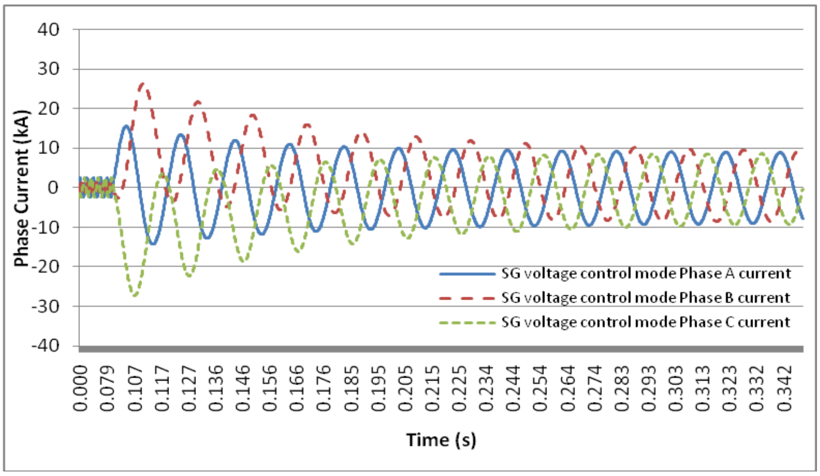

Figure 23 Voltage control mode - SG's dynamic behavior against 3P fault at Bus 5

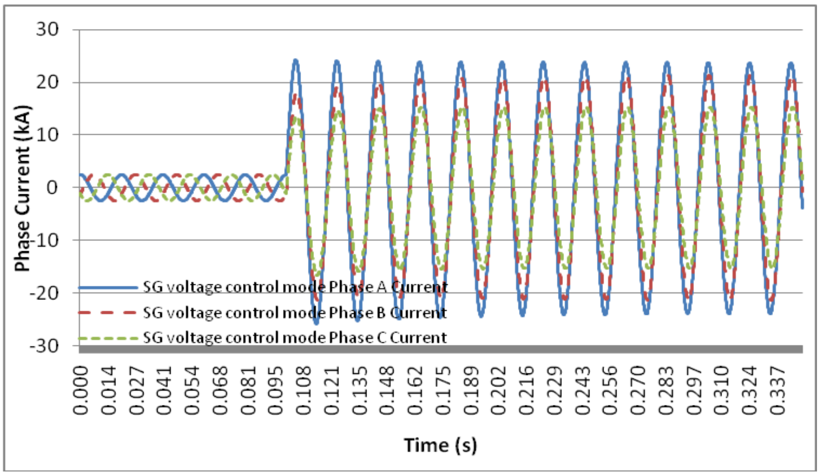

Figure 24 Voltage control mode - SG's dynamic behavior against L-G fault at Bus 5

For 3P fault, the fault level of SG with pf control mode reaches to 30 kA. The least fault current is supplied by AG. The pre-fault terminal voltages of the generator are listed in Table 23. The terminal voltage of SG with pf control mode is more than the terminal voltage of SG with voltage control mode. For the L-G fault, AG has very low short-circuit current. The short-circuit current value of the Phase A is nearly the same as the nominal value. But the other phase currents of AG are nearly half of the nominal value. The short-circuit current of all phases of SG with both pf and voltage control mode exceeds the short-circuit values of the 3P fault case.

Table 23 Pre-fault pu values of the terminal voltages of each generator

Generator Type	**Pre-fault Terminal Voltage (pu)**
AG	0.9861
AG with PFC	0.9814
SG pf control mode	1.0264
SG voltage control mode	1
Static Generator	0.9892

In the second part of the short-circuit analysis, as seen in Figure 25, different faults occurring at the first bus of the second feeder will be analyzed so that the fault current contribution of each generator and no distributed generator case is seen.

This analysis will show whether or not the protection element at the starting of the second feeder has to be changed or the settings of it have to be changed.

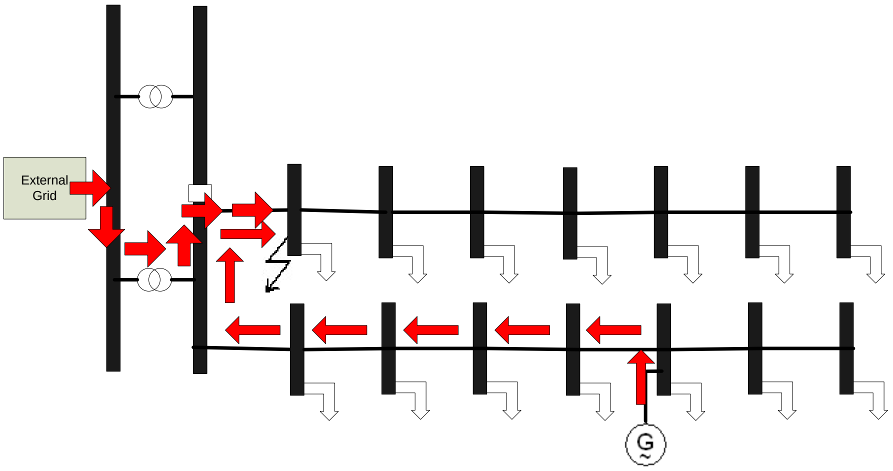

Figure 25 Contribution of sources to fault current

The values listed in

Table 24, are the peak short-circuit current values at the first bus of the second feeder, that is, they are not only the fault currents supplied by the distributed generators but also the upstream grid.

The short-circuit current passing through the faulted bus is 4.07 kA when there is no distributed generator and the fault is fed by the upstream grid. In presence of distributed generators, the worst contribution is supplied by SG with pf control mode and AG with PFC. In both cases, the generator supplies a constant amount of reactive power to the network. There is a considerable difference between the power ratings of these generators but the buses they are connected to are different. AG with PFC is closer to the fault point than SG with pf control mode. This makes the situation reasonable that the fault current from AG is same as those from SG with pf control mode although SG has 1.3 fold more power rating than AG.

Table 24 Peak short-circuit currents for different fault types in kA

	3P			L-L			L-L-G			L-G		
	PHASES			PHASES			PHASES			PHASES		
	A	B	C	A	B	C	A	B	C	A	B	C
No Generator	4.1	4.1	4.1	0	3.5	3.5	0	3.6	3.5	0.7	0	0
AG	4.1	4.1	4.1	0	3.6	3.6	0	3.6	3.5	0.7	0	0
AG with PFC	4.2	4.2	4.2	0	3.6	3.6	0	3.7	3.5	0.7	0	0
SG pf control mode	4.2	4.2	4.2	0	3.6	3.6	0	3.6	3.6	1.1	0	0
SG voltage control mode	4.1	4.1	4.1	0	3.6	3.6	0	3.6	3.6	1.1	0	0
Static Generator	4.1	4.1	4.1	0	3.5	3.5	0	3.6	3.5	0.7	0	0

3.6 Voltage Sags - Swells

Voltage sag is a short-duration reduction in rms voltage caused by faults on the power system and the starting of large loads, such as induction motors. Voltage sag is an event that can last from half of a cycle to several seconds (typically 0.5 to 300 cycles) [33]. Voltage swell is the converse of voltage sag. Voltage swell is a short-duration increase in the rms voltage between 1.1 and 1.8 pu with a duration of 0.5 cycle to 1 minute. A voltage swell could occur from the temporary voltage rise on the unfaulted phases during an L-G fault. Swells could also caused by switching off a large load or energizing a large capacitor bank. Customers in all sectors (residential, commercial, and industrial) have sensitive loads. Computer controls tend to lose their memory, and the processes that are being controlled also tend to be more complex and, therefore, take much more time to restart. Industries are relying more on automated equipment to achieve maximum productivity to remain competitive [34].

This shows that the occurrence of voltage sags-swells has negative impact on the power quality supplied by the distribution companies and could bring economical losses to customers with sensitive loads. The magnitude of the voltage sag is governed by the electrical distance of the observation point from the site of the short circuit and the sources of supply. The level to which the voltage falls at a particular observation point during the sag is a random value, depending on its position in the network relative to a short circuit [35].

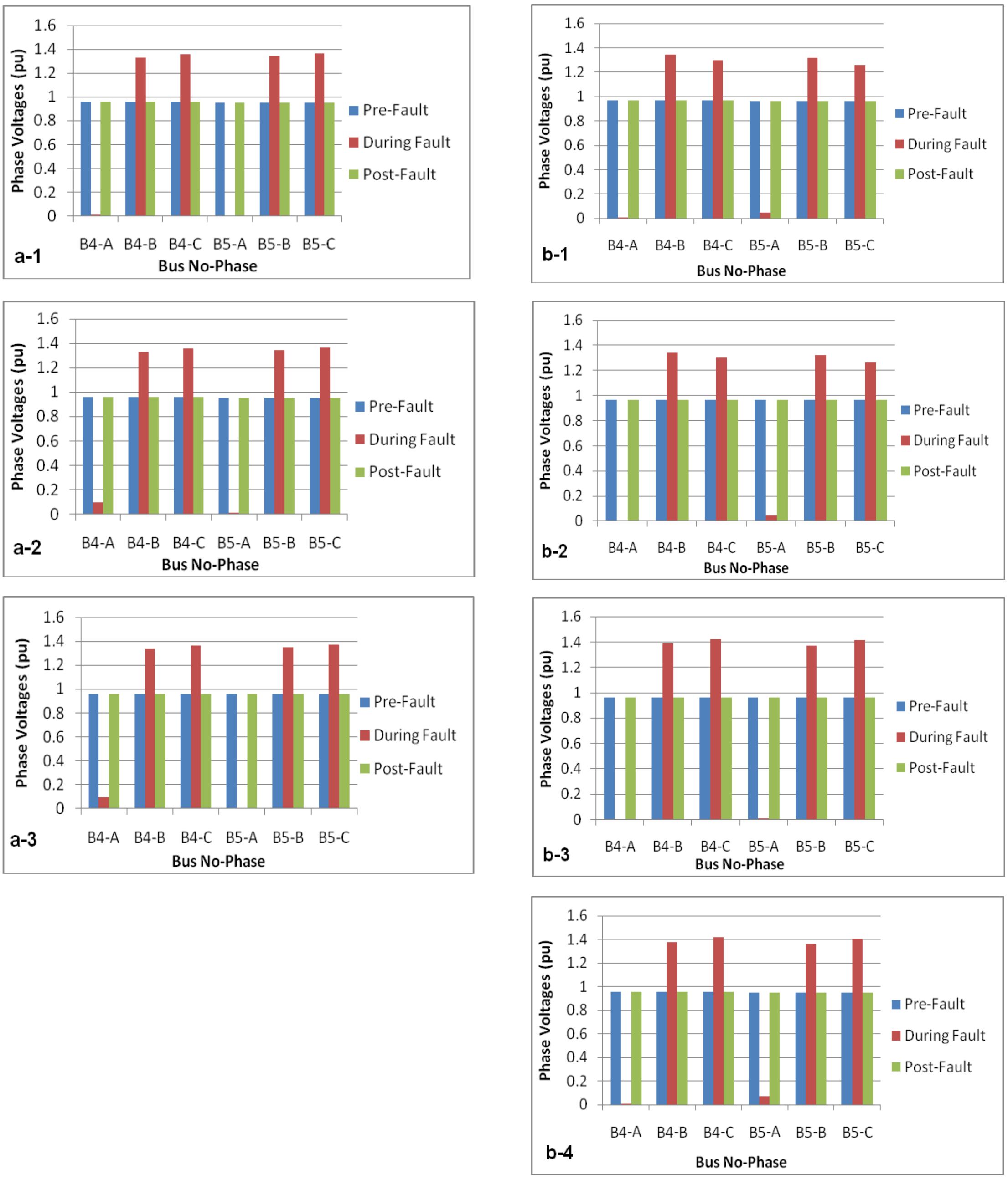

Figure 26 Phase voltages of Bus 4 and Bus 5 for L-G fault at Bus 5 of a-1) No Generation, a-2) AG and a-3) AG with PFC cases and L-G fault at Bus 4 of b-1) No Generation, b-2) SG with pf control, b-3) SG with voltage control and b-4) static generator cases

There are column charts consisting the phase voltage values of Bus 4 and Bus 5 for a L-G fault between Phase A and ground with a duration of 0.5 s in Figure 26. In the first column of the figure, the fault occurs at Bus 5 and the phase voltages are shown of no DG, AG without PFC, AG with PFC cases. The second column of the figure involves no DG, SG with pf control mode, SG with voltage control mode and static generator cases. The presence of distributed generators has increased the voltage magnitude in the unfaulted bus. The presence of distributed generators has brought no considerable change in voltage magnitudes of the buses in the power system.

Table 25 Voltage dip amplitude and duration values in various standardization documents, regulations and publications [36]

Standardized quantity	Amplitude	Min. duration	Max. duration
IEC 1000-2-1	10–100 % of U_N	0.5 cycle	Several seconds
IEC 1000-2-2		10 ms	3 s
IEC 1000-2-5	10–99 % of U_N	10 ms	Several seconds
IEC 61000-2-12		10 ms	3 s
EN 61000-4-11	10–95 % of U_N	0.5 cycle	Several seconds
IEC 1000-6-1	10–95 % of U_N		
IEC 1000-6-2	10–95 % of U_N		
EN 50160	10–99 % of U_N	10 ms	1 min
GOST 13109-97[29]	more than 10 % of U_N	10 ms	Several tens of seconds
UNIPEDE	10–99 % of U_N		
UIE	10–99 % of U_N	10 ms	1 min
IEC 61000-4-30	All threshold values are the subject of a contract		
IEEE Std. 1159-1995	10–90 %	0.5 cycle	1 min
CENELEC	10–90 %	10 ms	1 min
EPRI	< 95 %	1 cycle	1 min

In Table 25, there exists various standardization values on voltage dips. These values should be considered before preparing regulations about connection of distributed generators to distribution system. Although investigating the impact of distributed generators on voltage sags and swells, thus, on power quality is useful before permitting DG to connect to distribution network, voltage sag and swell analysis should be conducted, but this analysis will have secondary importance.

3.7 Transient Stability

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe disturbance such as loss of generation or a large load [37]. The system response to such disturbances involves rotor angle deviations in SG, terminal voltage and reactive power deviations in AG and variations in power flows and bus voltages. If the resulting angular separation between the generators and the whole system remains within the certain bounds after the disturbance is cleared, the system maintains synchronism.

The protection system in traditional radial-operated distribution systems is not designed for generation penetration and bi-directional power flow within distribution level. Once a fault occurs, it is necessary to consider the stability of the distributed generators [38]. When a distributed generator loses its stability, the adverse impacts of the generator could be seen such as drawing large amount of reactive power and causing the bus voltage to collapse. Since the inertia constants of these types of generators are low, it is possible for these generators to be affected severely during the faults which will be cleared by the relatively slow protection system of the distribution system.

In this part of the study, the transient stability behavior of distributed generators will be investigated. During a fault, SG's speed starts to increase until the disturbance is cleared. The rotor angle changes as the generator's speed deviates from the synchronous speed [37]. So, the rotor angle of SG will be analyzed for the transient stability issues. For AG, in case of a fault, these generators start to speed up and the reactive power drawn considerably increases. The rotor speed or the terminal voltage could be analyzed for transient stability analyses. Also, for the distributed resources utilized with a power-electronic interface could be evaluated from the transient stability point by considering the terminal voltage, active and reactive power variation of the inverter [39].

In the coming analyses, the sample distribution system introduced before will be used. A three-phase short-circuit will occur at the bus where the generator is connected and the fault will be cleared 500 ms later. The fault resistance is adjusted as 0.001 ohm.

In Figure 27, the bus voltages of AG with and without PFC could be seen for a fault which starts at t=0.1 s. and cleared at t=0.6s. It is seen that in both cases, the bus voltage after the fault is cleared, is 1 pu and AG keep their stability. AG with PFC settles down to unity bus voltage faster than the one without PFC but the bus voltage reaches to 1.2 pu after the fault clearance in AG with PFC.

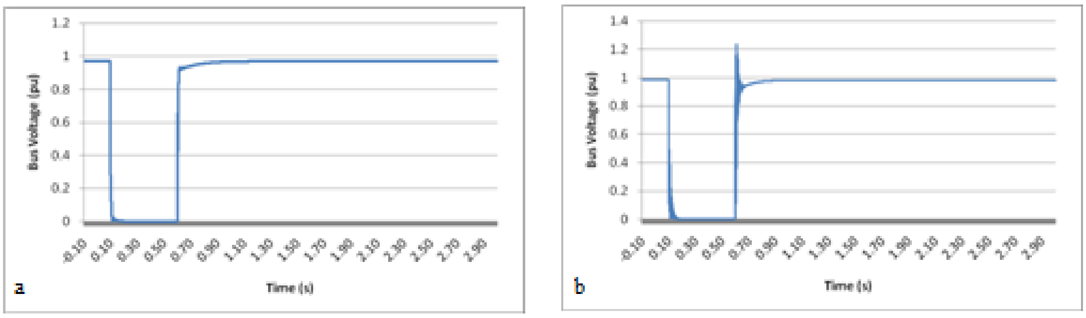

Figure 27 Bus voltages of a) AG without PFC b) AG with PFC

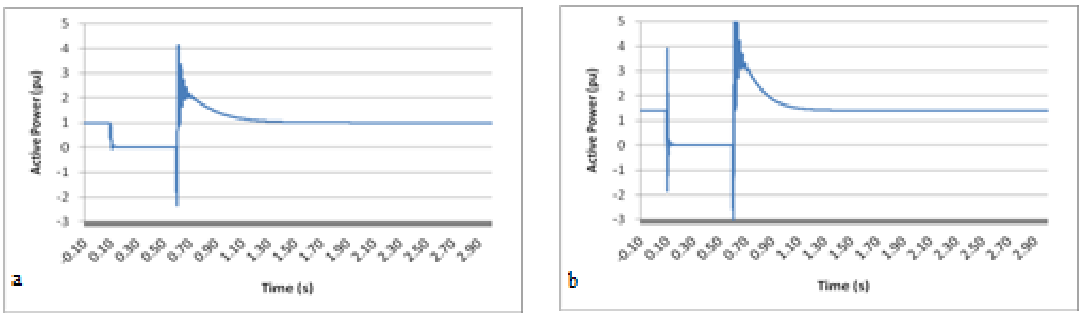

Figure 28 Active power variation of a) AG without PFC b) AG with PFC

In Figure 28 and Figure 29, the active and reactive power exchange between the generators and the network is shown.

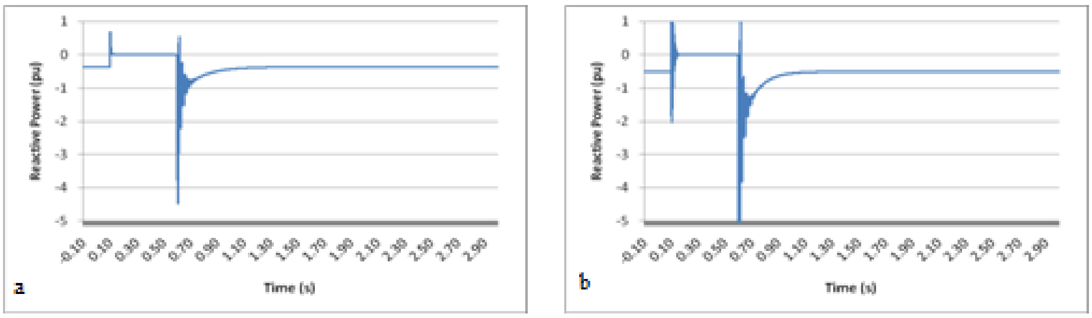

Figure 29 Reactive power variation of a) AG without PFC b) AG with PFC

The dynamic response of AG with PFC is seen to be greater for both active and reactive power during occurrence and clearance of the fault. Both cases, the generator keeps stability by supplying same amount of active and reactive power after and before the fault.

In Figure 30, the variation in rotor angle of SG with pf control mode and voltage control mode could be seen. The maximum rotor angle of both generators seem to be the same. But the fluctuation in the sycnhronous generator with pf control mode is far more larger. There are two dip points in this generator but there is only one dip point in SG with voltage control mode. However, both generators keep their synchronism after the fault is cleared.

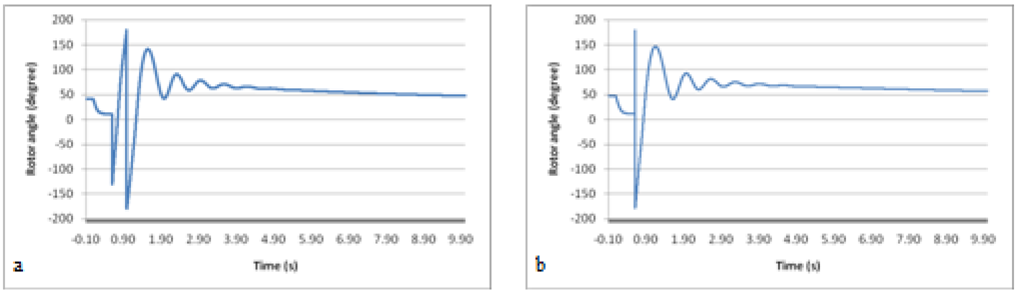

Figure 30 Variation in rotor angle of a) SG with pf control b) SG with voltage control with respect to local bus voltage

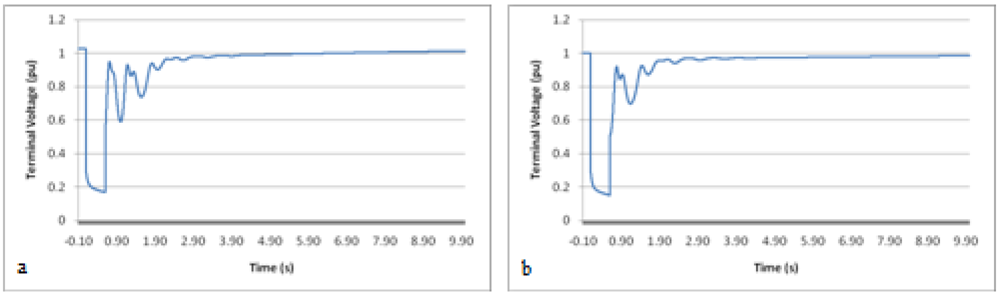

Figure 31 Variation in terminal voltages of a) SG with pf control b) SG with voltage control

Figure 31 shows the terminal voltages of the generators. During the fault, the terminal voltages of the generators drops below to 0.2 pu. As soon as the fault is cleared, the terminal voltages of the generators increases up to 1 pu, with again larger fluctuations in sycnhronous generator with pf control mode.

In Figure 32, the speed variation of SG could be visualised. The pf controlled SG's speed reaches up to 1.06 pu and the other generators's speed is about 1.05 pu at peak. Unless the generators are disconnected from the utility due to undervoltage protection function of the protection relays, both of these maximum speed values are sufficient to trigger the overspeed protection functions in protection relays and depending on the realy settings, most probably, both generators will be disconnected from the network due to overspeed protection.

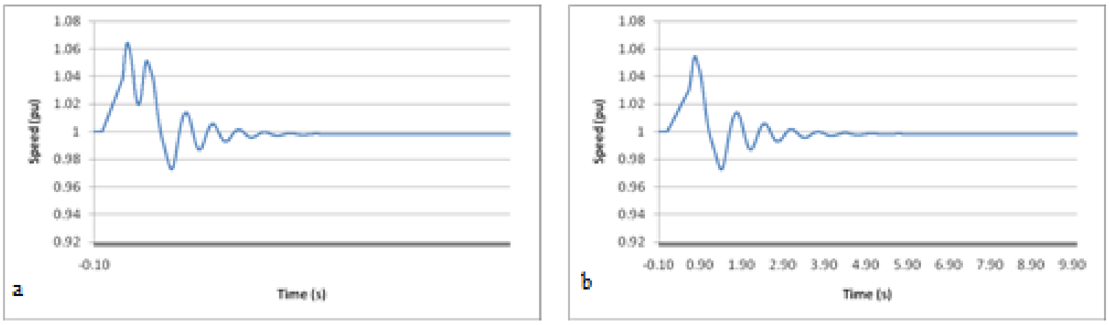

Figure 32 Variation in speed of a) SG with pf control b) SG with voltage control

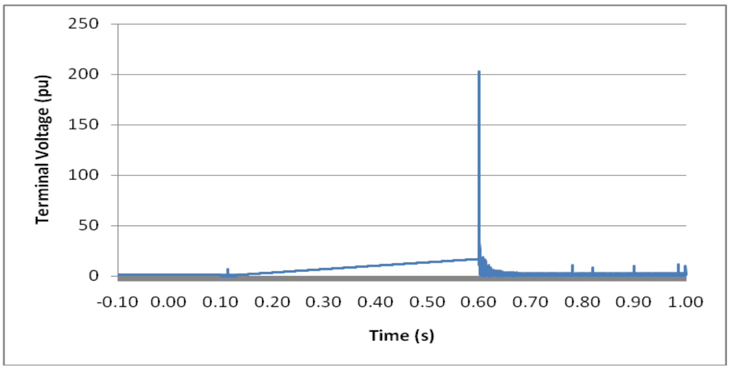

Figure 33 Terminal voltage variation of static generator

The terminal voltage of the static generator is shown in Figure 33. During the EMT analyses, there have been convergence problems, therefore, the duration of the simulation has been cut at t = 1 s. The terminal voltage value of the generator has reached to 200 pu which is not realistic in practical conditions.

Also, in Figure 34, the active and reactive power of the static generator could be seen. The active power output of the static generator reaches to 10-12 pu, which is again not a realistic value. These values show the convergence problems for these fault conditions.

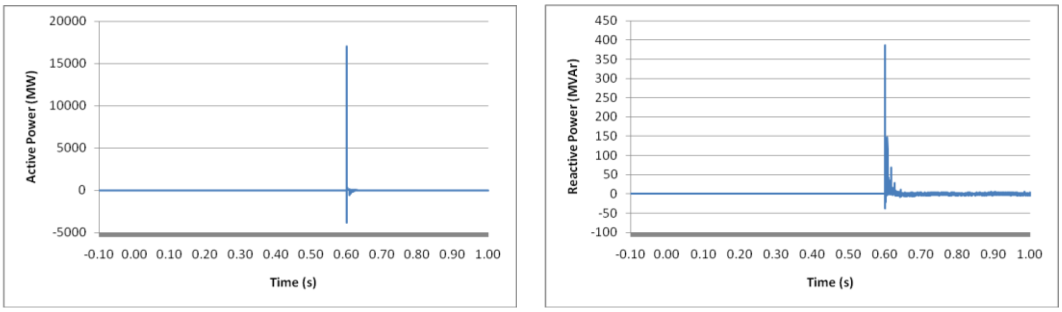

Figure 34 Active and reactive power variation of static generator

The reactive power supplied by SG with voltage control mode, increases during the fault and after the clearance of the fault, since the aim of this control mode is keeping the terminal voltage of the generator at the predetermined value. This helps to maintain the stability of the generator rapidly. For AG case, the reactive power is supplied to the network at the start of the fault, but after the clearance of the fault, a high amount of reactive power is drawn from the network, which could lead a voltage collapse at the system. The static generator should be immediately disconnected from the network, since at the clearance of the fault, the terminal voltage of the generator reaches at very high values.

3.8 Voltage Stability

Voltage stability may be described as the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance [37]. Voltage stability refers to loss of voltage. A system enters into voltage instability state when a disturbance causes an uncontrollable decline in voltage. The main factor that causes voltage instability is the inability of the power system to meet the demand for reactive power. Other factors influencing voltage stability are limitations of active and reactive power of generators, load characteristics, distribution system voltage regulator and substation tap-changer action, reactive power compensating device characteristics such as shunt capacitors or static VAr compensators.

Under normal operating conditions, the bus voltage magnitude increases as the reactive power injected at the same bus increases. Voltage instability occurs when voltage magnitude of any bus in the system decreases as the reactive power injection increases at the same bus [40]. The relation between the voltage magnitude and the power transmitted is considered when voltage stability is analyzed. The presence of distributed generators is expected to contribute to the voltage stability margin. But, the impact of distributed generators is a matter of reactive power exchange between the generator and the network. Therefore, the technology used for distributed generators is very critical for voltage stability. Commonly, PV curves are obtained from the results and the voltage stability is evaluated from this curve. This curve is obtained by keeping the active power injected by the distributed generator constant and varying the active and reactive loads in a bus.

The impact of DG could be investigated by using load flow sensitivity analysis. In this analysis, the effect of the injections of ΔP and ΔQ at the selected busbar for the whole network is evaluated [41]. The voltage variation versus active and reactive power at all buses is shown in Figure 35 and Figure 36. The higher voltage variation against ΔP and ΔQ indicates the greater tendency towards voltage instability. No DG case has the highest dV/dP and dV/dQ sensitivity and the presence of distributed generators of each type improves the sensitivity of all buses. The 1200 kVA- SG with voltage control mode makes the best contribution to the power system.

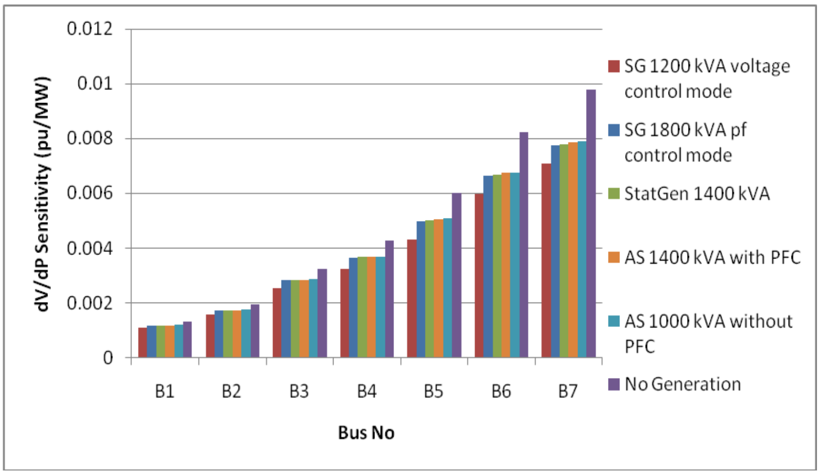

Figure 35 dV/dP sensivities of all buses with different DG cases

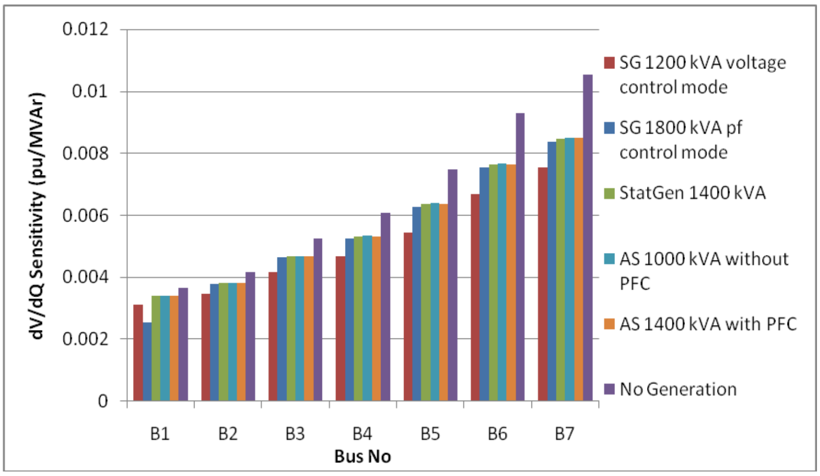

Figure 36 dV/dQ sensitivities of all buses with different DG cases

The figures above are very useful for evaluating the impact of distributed generators on voltage stability. In Figure 37 and Figure 38, the P-V curves of the Bus 7 with different distributed generators could be seen. In previous parts of the study, some generators have been decided to be connected at Bus 4 and some at Bus 5 due to line loss reduction. The generators in Figure 37 have been connected to utility at Bus 5 and the generators in Figure 38 have been connected at Bus 4. The load at Bus 7 has been increased until the program could not complete load flow calculation due to convergence problems.

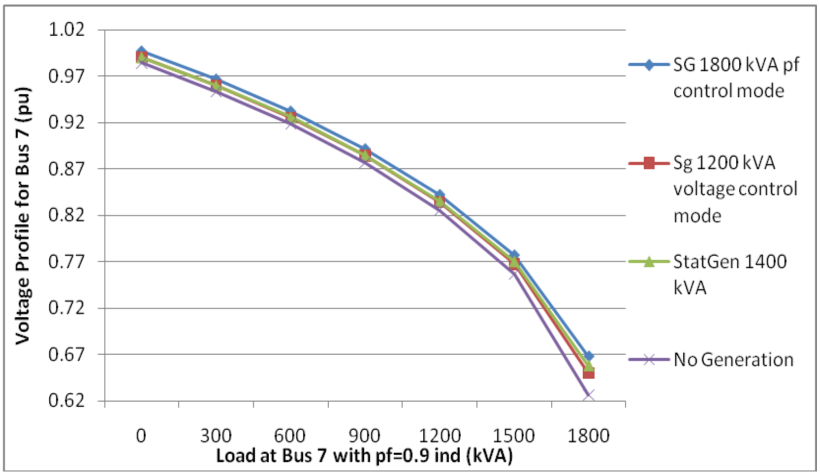

Figure 37 P-V curve of Bus 7 with distributed generators connected at Bus 5

The presence of the distributed generators connected to utility at Bus 5 improves the voltage profile of Bus 7 compared to no generation case. However, as seen in the figure below, the presence of AG has nearly no impact on the bus voltage compared to no generation case. Although the active power injected by AG improves the voltage profile, the reactive power drawn by these generators clears this positive effect.

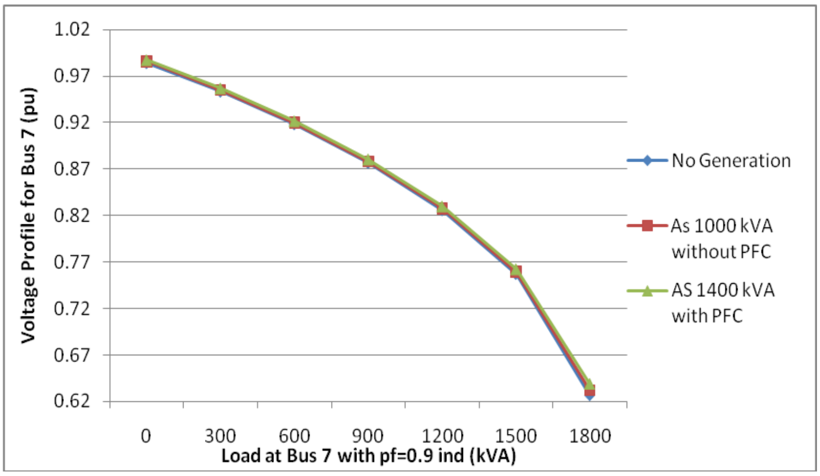

Figure 38 P-V curve of Bus 7 with distributed generators connected at Bus 4

Despite the positive effect of distributed generators on the load flow sensitivities and the voltage profile of the buses in the system, checking voltage stability as a prerequisite for the authorization of the connection of distributed generators to the utility is not necessary.

3.9 Protection and Interconnection Requirements

The primary mission of power system protection is to maintain the safe operation of power system. The safe operation of power system involves the safety of people, personnel and the equipment. Also, it is aimed to minimize the effects of unavoidable faults on the system equipment. During the installation of DG facilities, the proper protection of the utility, the distributed generator and the equipment should be ensured.

In this part of the study, the requirements for proper protection of the utility and the distributed facility will be investigated. It is very important to define the necessary equipment and the protective functions for this purpose. These equipments and functions should be requested from DG investors as prerequisites for the permission of the installation of these types of generation units.

Protection scheme could be classified as interconnection protection and generator protection. With the interconnection protection, the requirements of the utility for the connection of the generator are satisfied [44]. With the interconnection protection,

- The generator is disconnected when it is no longer operating in parallel with the utility.
- The utility is protected from the damages caused by the presence of the generator such as fault currents supplied by the generator.
- The generator is protected from the damages caused by the utility.

Similarly, with the generator protection, the generating unit is aimed to be protected. With the generator protection,

- The generator internal short-circuits are detected.

- The generator is protected from the damages caused by internal failures such as abnormal operating conditions such as loss of excitation, reverse power.

The presence of DG facilities in the distribution system could spoil the protection system philosophy, which is designed considering a passive distribution system with unidirectional power flow. However, with the increasing penetration of DG, the protection system could suffer from the possible problems explained below:

a. Loss of Coordination: The expected behavior of the protective devices in the power system is to detect and take action against the faults before their backup device operates. However, the presence of DG facilities could spoil the coordination between these devices. According to the protection philosophy in distribution system, this effect could happen between fuse-fuse coordination, recloser-fuse coordination and relay-relay coordination [42]. The increase in short-circuit level after the installation of DG facilities could lead to uncoordinated situations, depending on the location, size and type of DG unit.
b. Loss of Sensitivity: Sensitivity is the ability of protective devices to see the faults at the area of action of the device. Connection of DG units to the utility could lead to loss of sensitivity of the protection system. For instance, a fault at Bus 8 in the sample distribution system used will draw more fault current than the case without DG unit. Therefore, there is a risk of exceeding the setting and ratings of the protective devices. This event is the over-reaching of the devices [43]. However, the presence of DG units will decrease the fault current supplied by the utility. So, the protective device at the start of the feeder could not see the fault at Bus 8. The sample distribution system could be seen in Figure 6.
c. Bi-directionality of Protective Devices: Installation of DG units could lead to unnecessary loss of some loads due to the tripping of protective devices against fault current flowing to the upstream of the area of action of the device [23]. This phenomenon could be explained as in Figure 39 and Figure 40 . A fault in a Feeder 2 draws no current from the feeder.

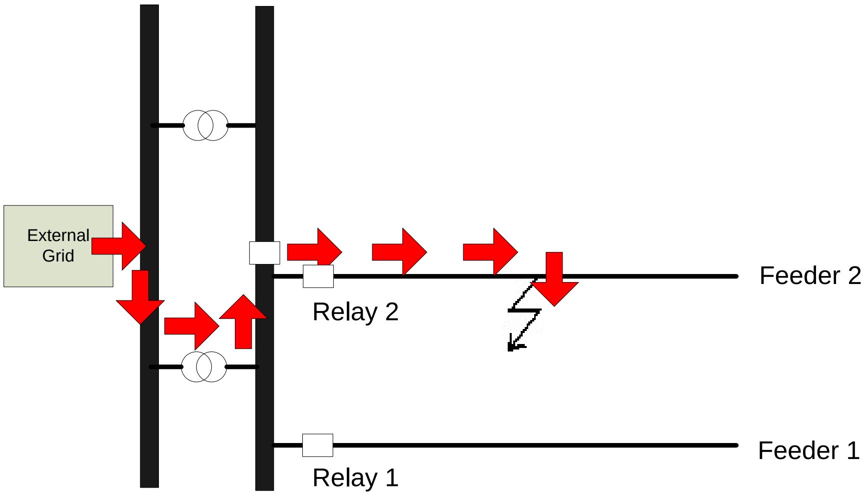

Figure 39 Fault current flow for no DG case

However, in presence of DG, the fault current supplied by DG unit passes through Relay 1 and if the relay is not directional one, the loads on the Feeder 1 will be lost when the relay trips.

d. Unintended Islanding Mode: DG facilities could be operated in island mode for increasing the reliability of the service. Although, especially for renewable energy resources, it is very difficult to handle island mode due to load-matching problems, if DG facilities start to supply loads without the presence of utility, the necessary settings and configurations for the protective devices need to be done.

e. Over-voltages: Depending on the grounding and transformer connections, it is possible that temporary over-voltages could occur due to ground fault conditions. Also, it is possible that high power injection of DG facilities could cause over-voltages. These potential overvoltage problems should be considered for the protection of DG units. Therefore, the selection of transformer connections of the generation unit is very important and should be done considering DG units' grounding. In the Appendix A part, the relevant information about transformer connections could be read.

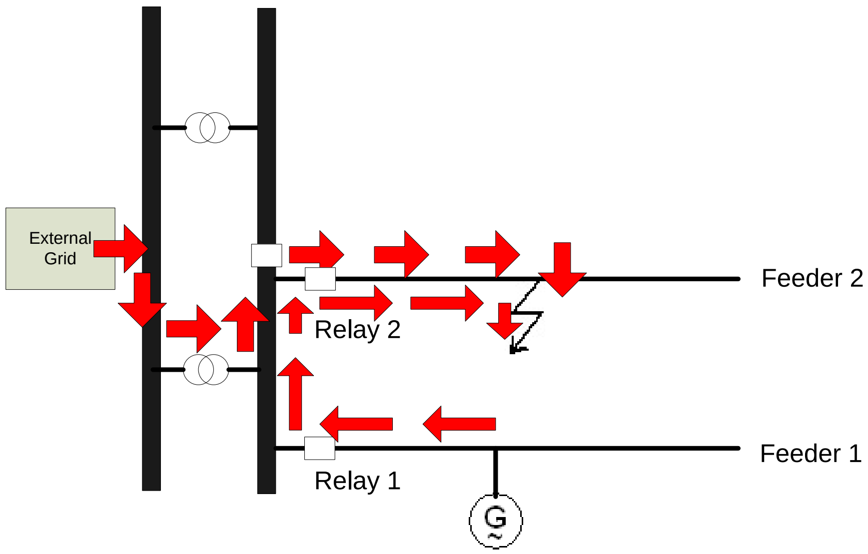

Figure 40 Fault current flow for DG case

3.9.1 Protection Methods for Interconnection of Distributed Generators

It is very important to determine the necessary protection functions for the connection DG facilities to the utility. The size, type, transformer configuration of DG unit affects the functional level of the protection. Below, the objectives of the protection system and the necessary protection functions will be explained:

a. Detection of Loss of Parallel Operation with Utility System: In presence of DG units in distribution system, a part of the network could continue operating as an island in case of sudden loss of grid connection. This is an undesired situation due to unsafe conditions for maintenance, risk of poor power quality for the loads in the island and complicated reconnection issues [43]. The most basic and universally accepted way of detecting loss of parallel operation with utility is using over/under frequency (81 O/U) and over/under voltage (27/59) protection functions. When DG unit starts to feed an islanded region, the frequency and the voltage will quickly violate the allowable limits valid for the utility when a difference between the output of the generation unit and the load occurs. In some application where rapid action is expected, the rate of change of frequency (81R) protection function could be used.

It is possible that during an island operation generation-load balance occurs and the allowable limits are not violated. For this possibility, it is necessary to use a transfer trip which needs a proper communication between DG unit and the substation.

b. Fault Back-Feed Detection: Small DG units' contribution to fault current is small and does not long too much. For this reason, fault backfeed detection systems are not installed to these facilities. But larger units' fault current is considerable and for preventing false operation of protective devices in the feeder, fault backfeed detection should be provided. Typically, protection functions such as directional overcurrent (67) distance (21) or voltage restrained overcurrent (51V) should be used for phase fault backfeed protection. Moreover, connections of the unit transformer determine the protection function to be used for ground fault backfeed.

c. Detection of Damaging System Conditions: It is possible that negative sequence current could flow through DG unit when unbalanced current conditions caused by phase reversals or open conductors occur. It is convenient to provide negative sequence current (46) protection function against this type of conditions. For phase reversals caused by inadvertent phase exchange after power restoration, negative sequence voltage (47) protection function could be used.

d. Reverse Power Flow Detection: Some DG facilities could have contracts in which the power to be sold to the utility is limited in time or amount. Therefore, it is frequent practice to install a directional power (32) protection function to trip DG unit if power inadvertently flows into the utility for a predetermined time.

e. Tripping/Restoration: Depending on the configuration of interconnection of DG facility and the utility and the matching of generation units with the local load, there are two restoration methods. If local loads would not be fed by DG units in case of utility failure, DG facility is fully disconnected from the utility preventing to feed local loads. Then, when the utility is restored, DG units are automatically synchronized to the utility with a synchrocheck relay (25), if required.

Table 26 Number and names of the protection functions

Function Number	Function
21	Distance
25	Synchronizing
27	Undervoltage
27N	Neutral undervoltage
32	Directional power
40	Loss of excitation
46	Negative sequence current
47	Negative sequence voltage
50	Instantaneous overcurrent
50N	Neutral instantaneous overcurrent
51N	Neutral time overcurrent
51V	Voltage restrained overcurrent
59	Overvoltage
59N	Neutral overvoltage
60FL	Voltage transformer fuse failure
67	Directional overcurrent
79	Reclosing
81	Frequency (over and under)
81R	Rate of change of frequency
87	Differential
LOM	Loss of mains

If the local loads are fed by DG units in case of utility failure, DG units are disconnected from the main grid but allowed to feed the local loads. In this case, when the utility is restored, to re-synchronize DG units, a more complicated synchrocheck relay should be used. This relay should check phase angles, slip and voltage difference between the utility and DG unit.

In Table 26, the protection functions names and numbers mentioned above are listed. The overall protection scheme could be visualized in Figure 41, which has been explained partially in above paragraphs.

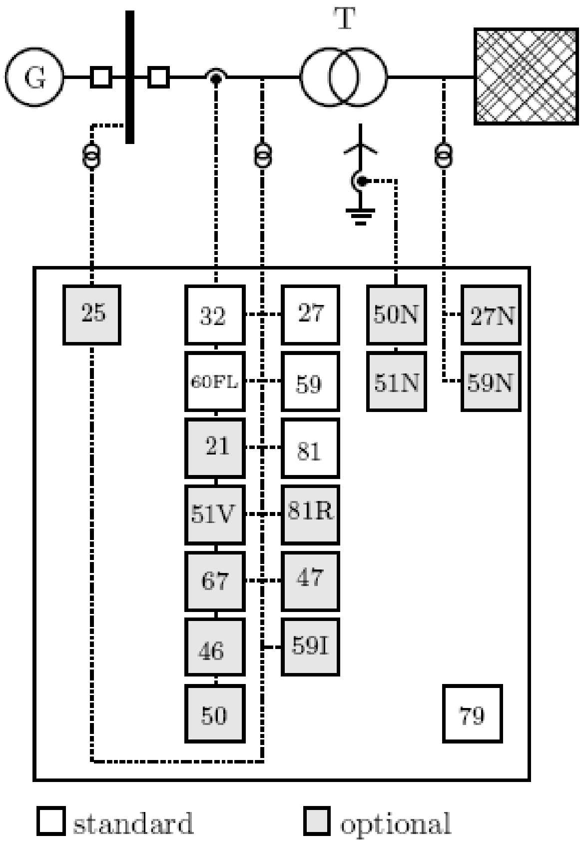

Figure 41 Typical multifunction relay with protection functions [26]

Added to the protection functions, the requirements below should be specified by the utility to the investors and engineers of DG facilities:

1. Current transformer and voltage transformer requirements
2. General requirements for connection relays
3. Winding configuration of the unit transformers
4. Speed of operation

3.10 Operating Reserves

In order to provide proper operation of the power system, system operators should balance the demand and generation of electricity over time horizons from seconds, through minutes, hours, days to weeks and even months ahead. The expected load should be predicted by short-term or long-term load forecasting and sufficient generation must be scheduled accordingly. Moreover, reserve generation should also be scheduled for the possible load forecast uncertainties, outages of generation plants, spontaneous load variations and generation forecast errors of poorly controllable power plants [45],[46]. In this part of the study, the impact of wind generation on reserve requirement in power system operation will be investigated.

The operating reserves could be classified according to time scales within they are operating as follows [47]:

a. <u>Contingency (Disturbance) Reserve</u>: 0-15 seconds. It is the online capacity for unforeseen equipment failure. The largest generator unit or the largest potential source of failure determines the contingency reserve.
b. <u>Regulating (Response, Instantaneous, Momentary, Primary) Reserve</u>: 15-90 seconds. This reserve type covers the reserve against fast fluctuations in the system load which is controlled by automatic generation control systems.
c. <u>Load-following (Secondary, Minute) Reserve</u>: 90 seconds-10 minutes. This type of reserve operates at slower time frames than regulating reserve. For providing load-following property, these reserve units are selected from those which are capable of quickly starting and synchronizing to the grid.
d. <u>Planning (Long-term) Reserve</u>: More than 10 minutes. With this type of reserve, both the operating requirements and planning purposes are covered.

3.10.1 Calculation of Required Operating Reserve

Conventionally, operating reserve requirements have been determined by rule-of-thumb methods. The most frequently used method is keeping a reserve equal to one or more largest units. However, this method could not consider all system parameters. In the operational phase, it could lead to over-scheduling which is uneconomic despite being more reliable or to under-scheduling which could be very unreliable although it costs less to operate.

As the penetration of renewable electricity generation units, especially wind and solar power, gets larger, the mismatch between load and generation will fluctuate much more. Now, the system operators will consider not only the changes in loads but also the fluctuations of the power output of these types of generation units, which could not be predicted in short-term estimation. This new situation brings the need of new reserve determination methods. Considering the uncertainties in the output power of renewable resources, a reserve determination method based on probabilistic approach would be more consistent and realistic.

There are many methods which have been proposed for determining the amount of required reserve. The Pennsylvania-New Jersey- Maryland (PJM) method was emerged from the need of determining the reserve requirement of PJM interconnected system. The basis of the PJM method is to evaluate the probability of the committed generation satisfying or failing to satisfy the expected demand during the period of time that generation cannot be replaced [48]. In [49], the probability of load changes and wind power uncertainties has been evaluated by establishing a relationship with reliability indices.

There exists another statistical method in which standard deviation of the wind generation time series is used. In probability theory and statistics, standard deviation is a measure of the variability or dispersion of a statistical population, a data set or a probability distribution [50]. It shows the average deviation from the mean value. A low standard deviation indicates that the data points tend to be very close to the mean, whereas high standard deviation indicates that the data are spread out over a large range of values.

Standard deviation of a time series could be calculated as follows:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \qquad (1)$$

where μ is the mean value of the series,

χ_i is the ith element of the series,

N is the number of elements in the series,

σ is the standard deviation.

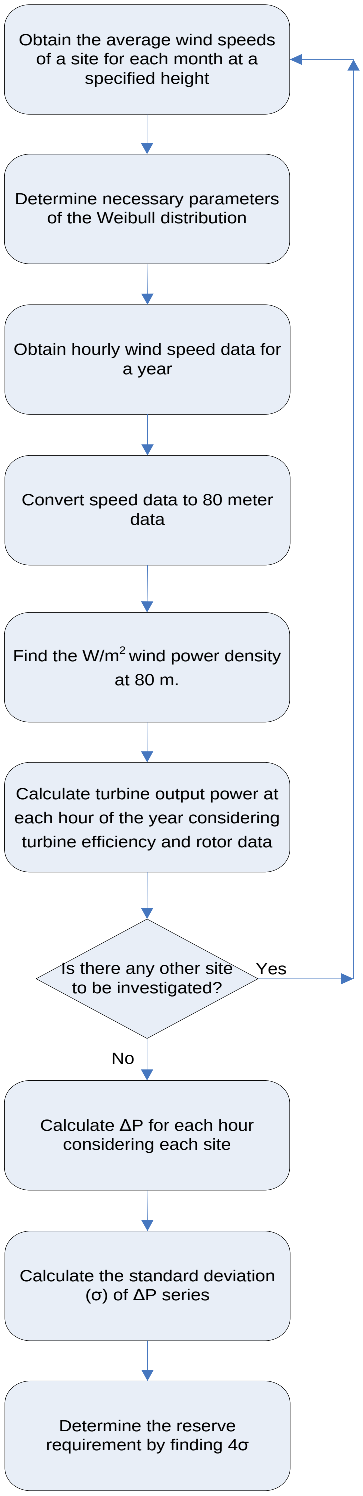

Figure 42 Method for the determination of reserve requirement

The reserve determination method in which the standard deviation is considered as an indicator is explained in Figure 42.Weibull distribution has two parameters, one is the shape parameter (k) and the other is the scale parameter (c). When the shape parameter is chosen as k = 2, this special distribution is called Rayleigh distribution. Rayleigh distribution is widely preferred in wind researches since the shape parameter is often found to be around k = 2. In Figure 43, a sample Weibull distribution could be found. Below, the Weibull distribution function could be seen:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

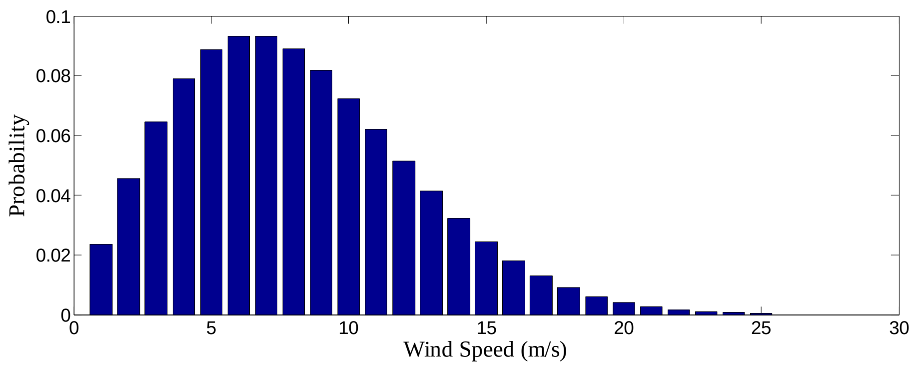

Figure 43 Sample Weibull distribution plot with for k = 2 and c = 9.14

In this study, the shape parameter has been taken as k = 2, that is, a Rayleigh distribution has been used. In order to estimate the scale parameter of the Weibull distribution of a specific site, the *wblfit* function of the Matlab Statistics Toolbox has been used. This function returns the parameters and parameter intervals of the Weibull distribution for the given wind speed values.

The next step is to obtain the hourly wind speed data which follows the Weibull distribution during a year. This corresponds to 8760 wind speed values. For this purpose, the *wblrnd* function of Matlab Statistics Toolbox has been used [52]. This function generates random numbers for a given Weibull distribution with given Weibull parameters. Since the characteristic of wind could not be estimated in hour-by-hour basis, the usage of random numbers fitting to the Weibull distribution is reasonable.

After getting 8760 values fitting to the Weibull distribution of the specific site, it is necessary to extrapolate these values into the 80 m. height. For this purpose, the expression below has been used [53].

$$\left(\frac{v}{v_0}\right) = \left(\frac{H}{H_0}\right)^{\alpha} \tag{3}$$

where v is wind speed at height H in m/s,
v_o is the wind speed at height H_o in m/s, in this study H_o = 10 m,
α is the friction coefficient which is taken as 1/7 for rough approximations.

The next step is to calculate the wind power density at 80 meters. Wind power density gives the potential power that could be obtained from that site in W/m^2. For Rayleigh distributions, below expression is used for establishing a relationship between the average wind speed and the average power density:

$$\overline{P} = \frac{6}{\pi} \cdot \frac{1}{2}\rho\overline{v}^3 \tag{4}$$

where ρ is the standard air density kg/m^3
v is the average speed in m/s
$\overline{P}$ is the average power density in W/m^2

After obtaining the average power density for a specific site, the power output of the wind turbine will be calculated considering the efficiency of the turbine and generator and the dimensions of the rotor. Below, the expression for getting the power output of the wind turbine is found.

$$P = \overline{P} \,.\, \pi \,.\, r^2 \,.\, \mu \qquad (5)$$

where $\overline{P}$ is the average power density in W/m^2

r is the length of the rotor blade in meters

μ is the efficiency of the wind turbine

At the end of this procedure, the hourly power output values of the wind turbine have been obtained. The number of wind turbines could be multiplied by the average wind power of a single turbine in order to calculate the total hourly generation of the wind site.

For a specific wind generation region, the hourly change in generation could be calculated as:

$$\Delta P_{wg,i} = P_{wg,i+1} - P_{wg,i} \qquad (6)$$

where $P_{wg,i}$ is the generation of the wind facility at hour i in W,

$\Delta P_{wg,i}$ is the difference between the generation values of hours (i+1) and i in W.

If the number of wind sites is more than one, it will be necessary to sum all of the ΔP of each site to form the hourly generation variation time series.

The generation variation time series, whose standard deviation value will indicate the amount of reserve requirement, consists of the hourly changes of the generation of the wind sites. The regulating and load-following reserves could be determined considering the hourly changes in wind generation because these reserves cover seconds to minutes. Obviously, the evaluation of changes in minute base will result in more precise reserve amounts but this will bring the data acquisition and processing problems due to the large number of data for an annual reserve assessment.

Following the acquisition of hourly generation variation time series, the standard deviation (σ) of this series will be calculated. As seen in Figure 44, one σ covers the ± 34.1 % of the variations from the mean value in a normal distribution. Some companies, such as EnerNex and Idaho Power in United States, offer to use 2σ for determining load-following reserves in wind applications covering approximately ± 47 % of the variations [47]. However, for maintaining the proper reliability of the power system, 3σ or 4σ values, which cover 99 % or 99.9 of the variations respectively, are preferred in order to determine the amount of required reserve. Therefore, in this study, 4σ value will be taken as the reserve requirement.

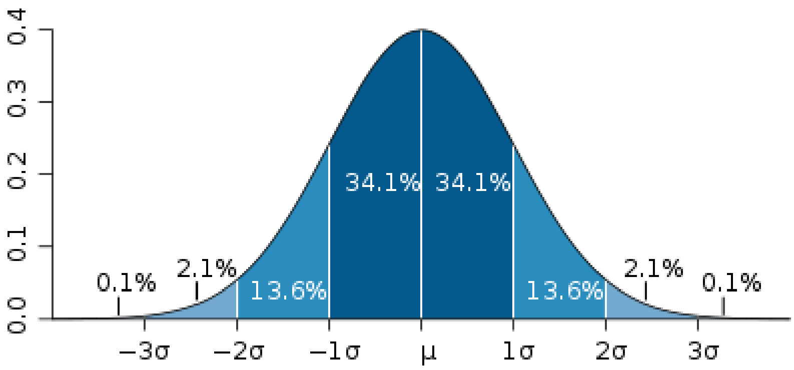

Figure 44 A plot for normal distribution divided with σ widths [50]

The considerable wind potential of Turkey is being converted into electrical energy rapidly by wind investments. As the economics of wind energy improves, the investments on wind power will increase. In Appendix C, the location, operation date and installed power of different companies' wind investments in Turkish power system could be seen. According to the Table C.1, after the first quarter of 2010, the total installed wind capacity will reach to 1575 MW, 4 % of the total installed capacity of Turkey.

In Table 27, the distribution of the installed capacity among the provinces and the monthly average wind speed data of that province are listed. The geographical locations of all provinces have been marked on the Turkey map in Figure 45.

Table 27 Installed or planned wind turbines' capacities and monthly average wind speed in different provinces

Province	Capacity (MW)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
İzmir	307.90	6.0	6.6	5.8	4.5	4.3	5.4	5.6	5.9	5.3	5.5	4.3	5.9
Çanakkale	112.00	7.1	6.6	6.2	4.6	5.9	6.6	5.7	8.1	6.8	7.5	5.2	6.6
İstanbul	86.05	7.2	6.8	6.5	4.4	4.3	4.7	4.2	7.9	6.9	7.4	5.5	7.2
Balıkesir	416.40	7.7	9.3	8.2	6.0	6.7	6.9	6.0	8.2	7.6	7.0	5.7	9.3
Manisa	297.60	4.2	6.2	7.3	4.8	4.9	7.3	8.7	9.0	6.2	5.0	5.0	6.6
Hatay	87.60	6.3	6.3	11.4	8.4	6.5	7.2	8.7	7.8	7.4	6.4	7.7	7.6
Mugla	28.80	5.7	5.5	5.8	6.4	5.3	6.7	5.9	5.8	6.9	4.8	3.7	3.4
Aydın	31.50	4.5	5.8	5.9	3.4	4.0	5.0	4.7	4.3	4.1	4.0	4.2	4.7
Osmaniye	135.00	8.8	9.7	8.1	6.3	6.9	9.7	8.1	9.8	7.3	7.9	6.4	9.3
Tekirdag	57.60	5.4	4.7	5.0	4.7	4.0	3.7	4.9	3.8	4.2	4.8	4.2	2.7
Edirne	15.00	5.0	6.6	5.4	4.7	4.6	5.3	4.6	4.5	4.3	4.2	5.5	5.2

Figure 45 Geographical distribution of wind sites in Turkey

In Table 28, the provinces included in the numbered scenario, the geographical distribution of the provinces in the scenario and the installed capacities of each province have been listed. In Scenario 1, all the 1575 MW-installed capacity is thought to be placed in Balıkesir. In Scenario 2, 1575 MW-capacity has been shared among three provinces, Balıkesir, Muğla and Edirne. In Scenario 3, 315

MW capacities have been installed in five provinces, summing up 1575 MW, Çanakkale and Hatay have been added to the provinces in Scenario 2. In Scenario 4, the number of provinces included has raised to 10. In Scenario 5, Aydın has been added to the provinces in Scenario 4. In Scenario 6, the provinces in Scenario 5 have been included but the uniform distribution of capacities no longer exists. Each province has the installed capacity listed in Table 27.

Table 28 Data of the different scenarios with included provinces and the installed capacity

Scenario	Location at Map	List of Provinces	Installed Capacity of Each Province
1		Balıkesir	1575 MW
2		Balıkesir, Muğla, Edirne	525 MW
3		Balıkesir, Muğla, Edirne, Çanakkale, Hatay	315 MW
4		Balıkesir, Muğla, Edirne, Çanakkale, Hatay, İzmir, İstanbul, Manisa, Tekirdağ, Osmaniye	157.5 MW
5 & 6		Balıkesir, Muğla, Edirne, Çanakkale, Hatay, İzmir, İstanbul, Manisa, Tekirdağ, Osmaniye, Aydın	143.18 MW & as shown in Table 27

Following the method defined previously in this study, the amounts of reserve requirements for each scenario have been listed in Table 29. The results show the positive impact of the geographical distribution of wind turbines on reserve.

Table 29 The required reserves in MW for different scenarios

Scenario	σ (MW)	4σ (MW)	% of Total Installed Capacity
1	321.73	1286.92	81.71
2	122.99	491.96	31.24
3	113.56	454.24	28.84
4	78.38	313.52	19.91
5	70.37	281.48	17.87
6	108.49	433.96	27.55

When all the capacity is installed at a site, the required reserve is around 80 % of the installed capacity, whereas, as the geographical distribution of the wind power plants increases, the amount of reserve decreases. When the same amount of capacity is shared between 11 provinces, the required reserve decreases to about 30 % of the total capacity.

3.10.2 Usage of Hydropower Plants as Backup Generation for Wind Power Plants

In the previous part of the study, it is seen that geographical distribution of wind turbines through large areas decreases the required operational reserve and thus increases the tolerance of the power system for higher penetration of power plants with variable output power such as wind power plants. Among the power plants, hydropower and gas power plants are fast responding plants and these types of plants are planned to be used as backup for changes in the output power of renewable power generation units. Turkish power system has large hydropower and gas power plants. Very few of the gas power plants are owned by the government, whereas, most of the large hydropower plants are public property. Moreover, most of the gas power plants have take-or-pay agreements and this complicates the usage of these facilities for backup power for renewable power generation. Therefore, it is convenient to facilitate large hydropower plants as backup generation against the changes in the output power of renewable generation units. The response times of hydropower plants' governors and turbines determine whether the required reserve for wind power will be provided against fast changes in output power of wind power plants.

In order to evaluate whether hydropower plants' response times could satisfy the required backup for the fast power changes in wind generation, a system model consisting of hydropower generation, wind power generation, load and secondary controller, has been created using Matlab/Simulink, as could be seen in Figure 46.

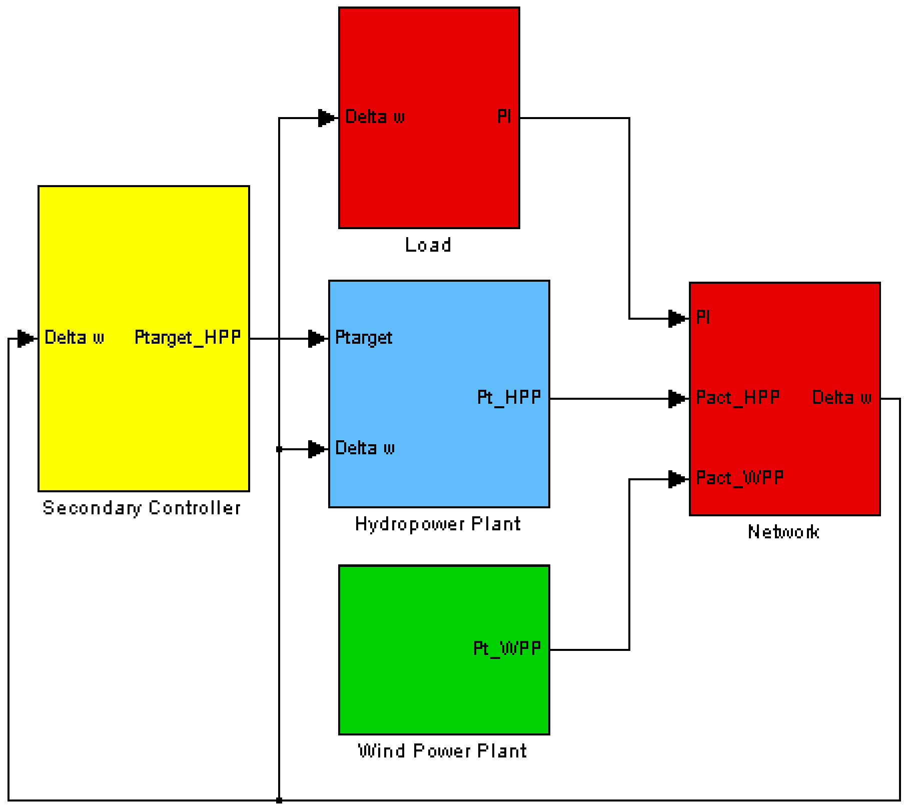

Figure 46 Hybrid system model including wind and hydropower generation

The load model involves a constant system load and effect of frequency change on load. The hydropower plant model consists of three major components: power controller, governor and turbine. In power controller part, actual generation is compared with target generation received from secondary controller and generation response for frequency change and a wicket gate opening set point is sent to the governor part of the model. Governor part receives the wicket gate opening set point and by using servo and pilot motors, the wicket gates are opened at that set point. Finally, the output power of the turbine is determined by actual wicket gate opening, water flow and pressure. Since the primary and secondary controls without considering transient responses are investigated, a mid-term dynamic model excluding generator model has been used [54].

In wind turbine model, output power measurement of a real wind power plant is transferred from the workspace. Thus, the measured power of a real wind power plant is sent to the network model, in which the load is extracted from generation and the integral of this difference determines the change in network frequency. In secondary controller model, the change in frequency is evaluated by a PI controller and the target output power of the hydropower plant is determined.

In this model, since the load is held constant, the change in output power of the wind power plant is compensated by hydropower plant. The total installed capacity is composed of 50 % hydropower and 50 % wind generation. At the start of the simulation, the loading of hydropower plant is 0.5.

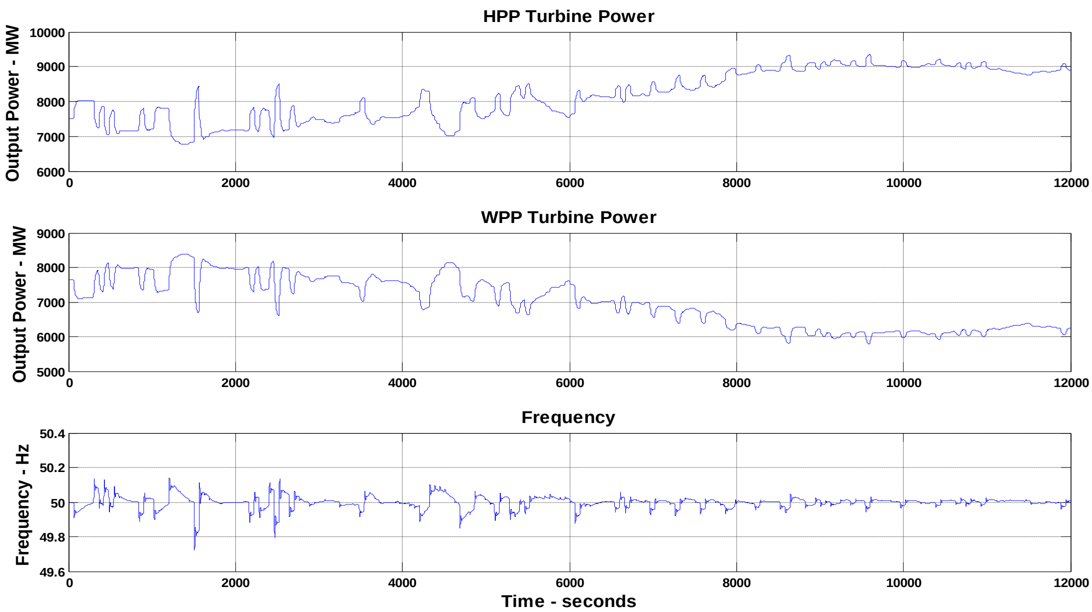

Figure 47 Hydropower and wind power plants' outputs and frequency response for the hybrid system model

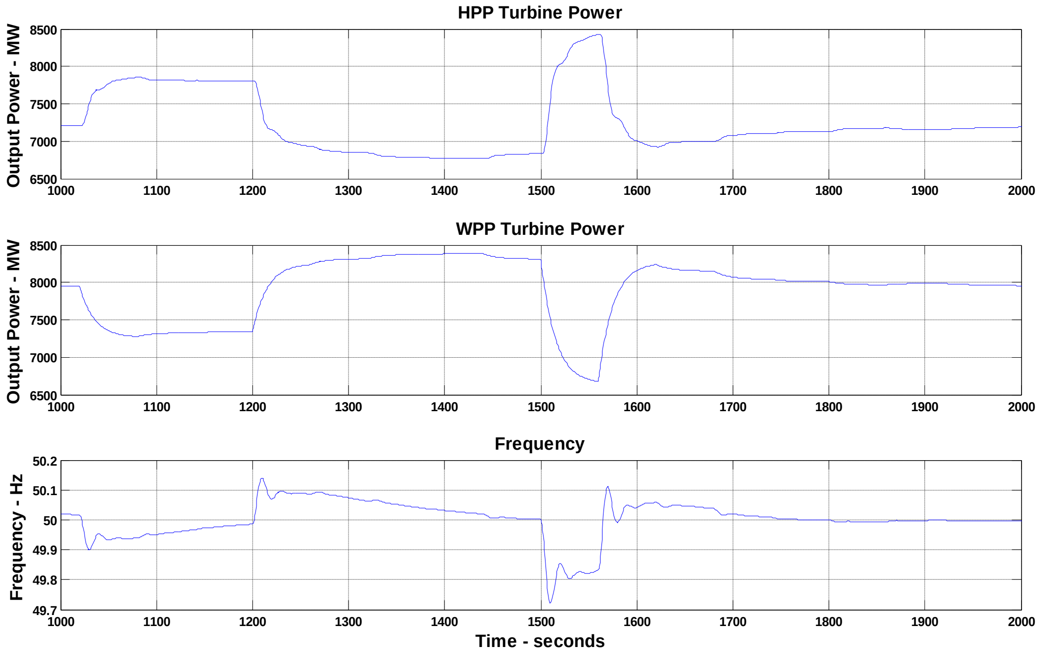

Figure 48 Response of hydropower plant against sharp power variations of wind power plant

The power outputs of hydropower and wind power plants with the frequency of the network for 12000 seconds could be seen in Figure 47. Even for the changes in wind power about 1500 MW in a minute, the hydropower plant takes over the remaining load and that keeps the network frequency in allowable limits. Figure 48 shows that hydropower plants are capable of providing backup generation for wind power installations considering the response times of the hydropower plants against the fluctuations in wind power.

However, today's power systems do not consist of only wind and hydropower plants. Thermal and gas power plants, also, contribute to power generation, as well. The secondary control mechanism provides the balance between generation and load in order to keep the frequency at 50 Hz. In case of load or generation change, the secondary controller determines the new operating points for the generation units which allocate reserve for secondary control. In Figure 49, the present secondary control mechanism with different power plants could be seen. In addition to Figure 47, the model includes the gas and thermal power plant parts.

Table 30 Generation capacities of different types of power plants in Turkish power system

	Installed Capacity (MW)	Available Capacity (MW)	Contribution to Frequency Control (MW)	Loading %	Reserve (MW)
Gas Power Plant	14300	12900	5.16	0.925	0.387
Thermal Power Plant	12000	7200	1.08	0.8	0.216
Hydropower Plant	12000	9600	3.84	0.8	0.768
Total	38300	29700			1.371

The gas power plant's model consists of power controller and governor. The thermal power plant model includes power controller, governor and turbine model. The balance between generation and load determines the deviation in frequency as an output of network block. This time, network block includes the amount of constant generation, which is the generation of different power plants that do not contribute to frequency control. In Table 30, the generation capacities and reserve contribution of each power plant in Turkish power system has been listed. With the model in Figure 49, a 4000-MW wind power penetration, which is the up-to-date total licensed wind power plants in Turkey, has been analyzed.

After a change in wind power generation, the secondary controller sends the target generation point for each power plant. As could be seen in Figure 50, sharp variations of wind power result in frequency changes about 80 mHz. But generally, the present secondary control mechanism handles the presence of wind generation and keeps the frequency under allowable limits.

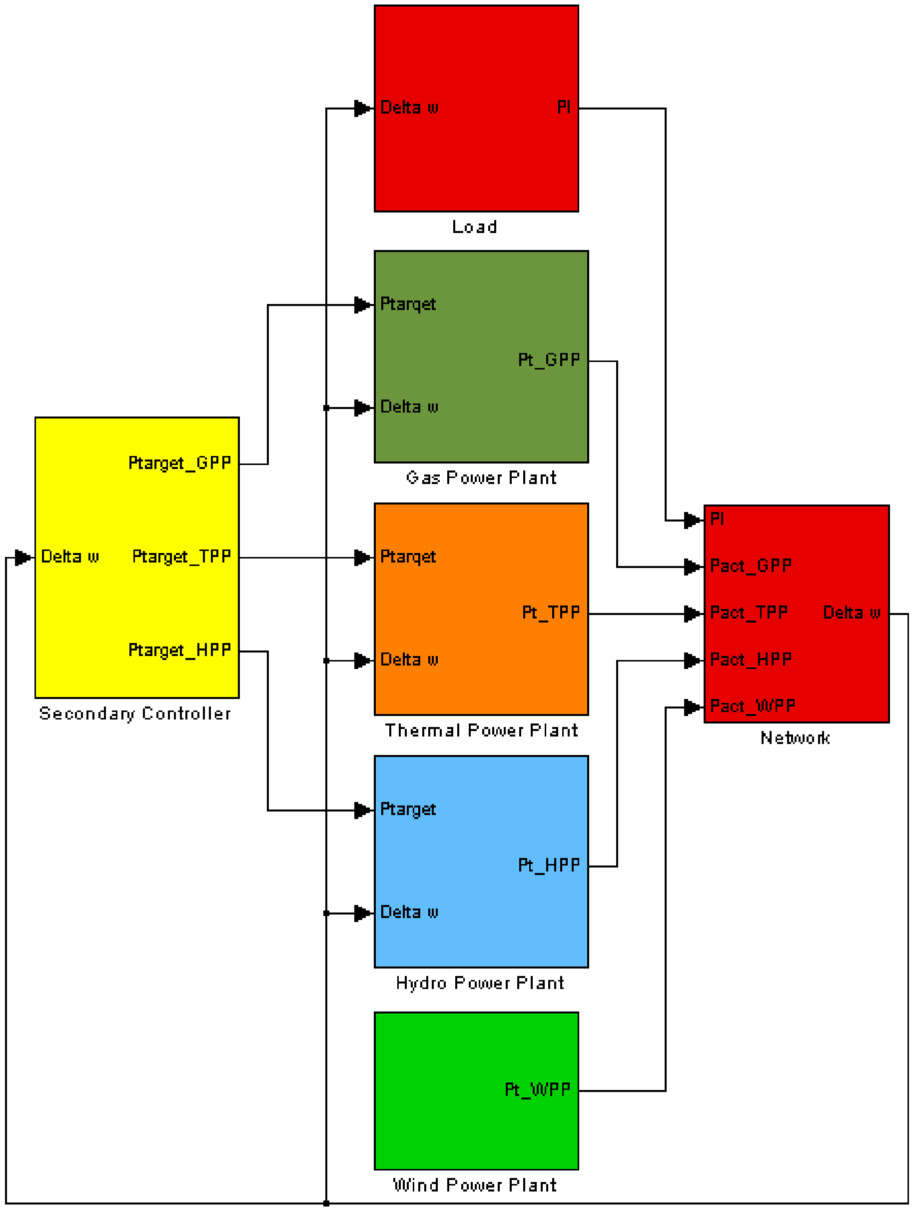

Figure 49 Present secondary control mechanism of Turkish power system in presence of wind power plants

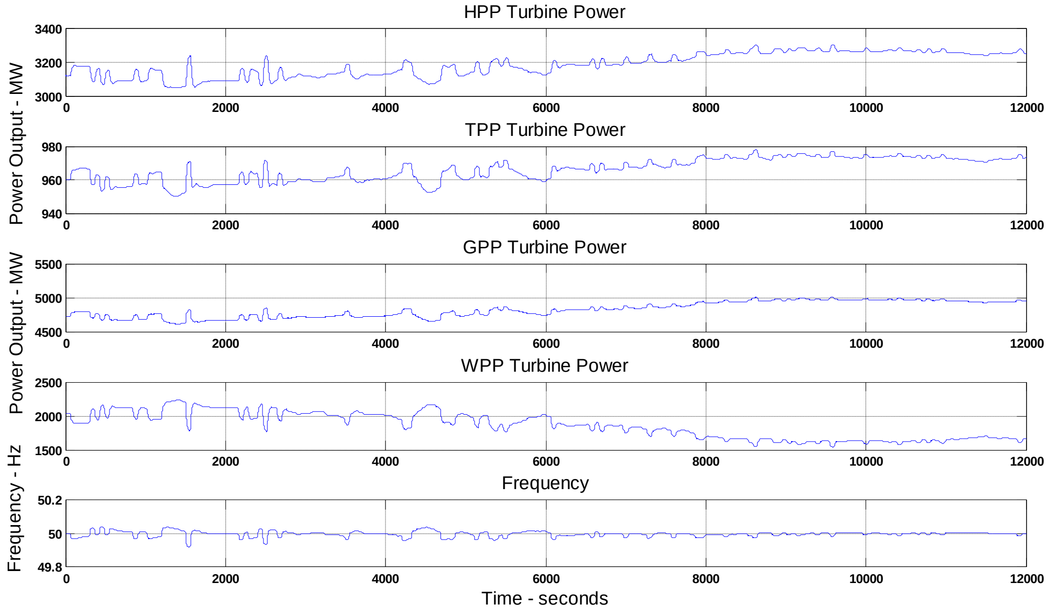

Figure 50 Power variations of different types of power plants and frequency of the network

It will be very useful to facilitate a wind secondary control mechanism just after all wind power plants' output power data is available and could be received by the dispatch center instantly. Since most of the gas power plants are not public property and have take-or-pay agreements, this wind secondary controller should use the hydro power plants, which could be allocated for this purpose by the public. In Figure 51, the addition of a wind secondary controller could be seen. The wind controller receives the output power of all wind power plants and sends target generation point to the dedicated hydropower plants. The response of the wind controller is set to be faster than the main secondary controller.

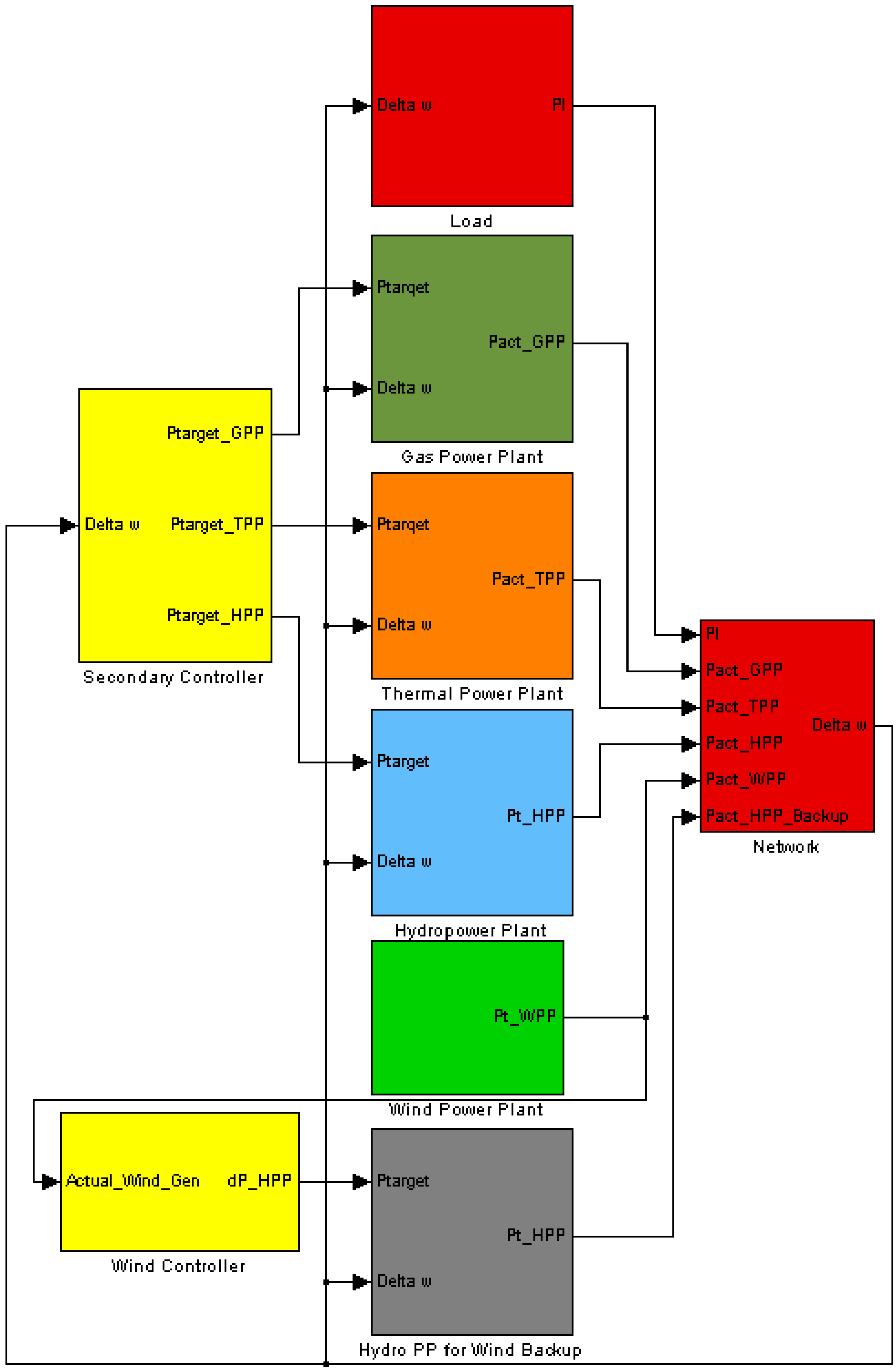

Figure 51 Addition of wind secondary controller into the Turkish power system

The variations in output power of each power plant and the change in frequency after the wind secondary controller block has been added to the present power system model could be seen in Figure 52. The backup hydropower plant takes over the loading when there exists a decrease in the output power of wind power plant. The frequency is hold at allowable limits. The changes in other power plants' outputs are due to the frequency variations caused by the imbalances between the wind power and the backup hydropower plants' generation since there is no load change in this simulation.

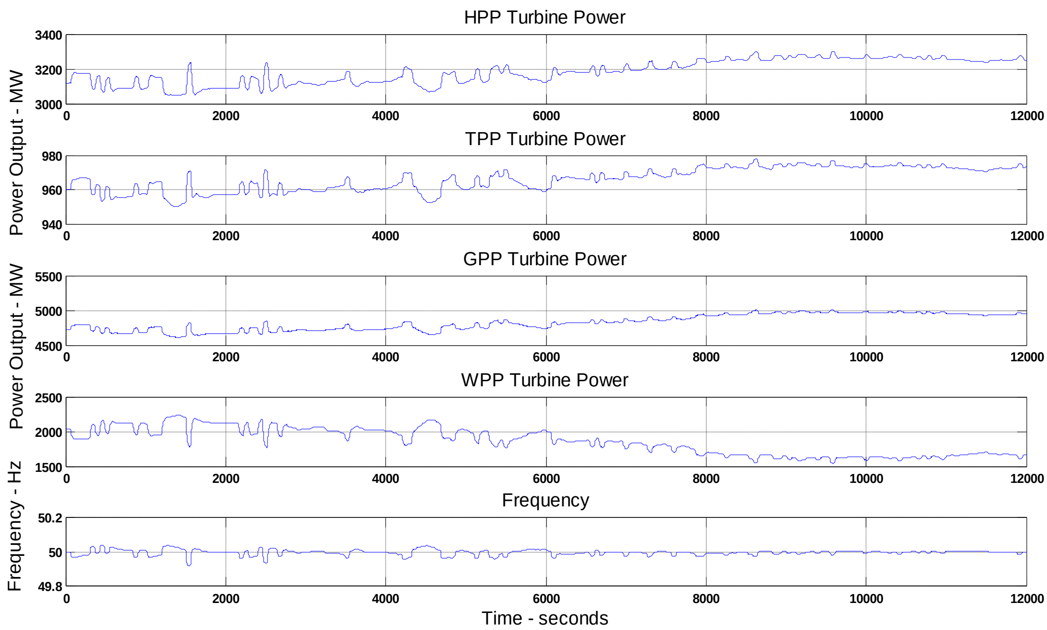

Figure 52 Power variations of different types of power plants and frequency of the network after the addition of wind secondary controller

3.11 Proposed Rule

In the previous studies of this chapter, many different technical impacts of DG have been analyzed on a sample distribution system. These technical analyses were:

- Line Loading
- Steady-State Voltage Profile
- Short-Circuit Current
- Power Quality Issues
- Transient Stability
- Voltage Stability

All of the analyses could be used for the investigation of the convenience of interconnection of DG to distribution system. However, among these analyses, some will be unnecessarily extra for the distribution authority for the authorization of the interconnection.

Transient stability analysis could be skipped during this process since this analysis needs a detailed model which would be different for each generator with different excitation and control mechanism. In order to develop a plant model for transient analysis, power plant parameters including excitation and governor or controller parameters, should be collected. This will extend the authorization time and increase the burden of the distribution authority.

The penetration of DG units in power system improves the voltage stability or the load flow sensitivity of the system, but the voltage stability analysis need not be a part of the procedure.

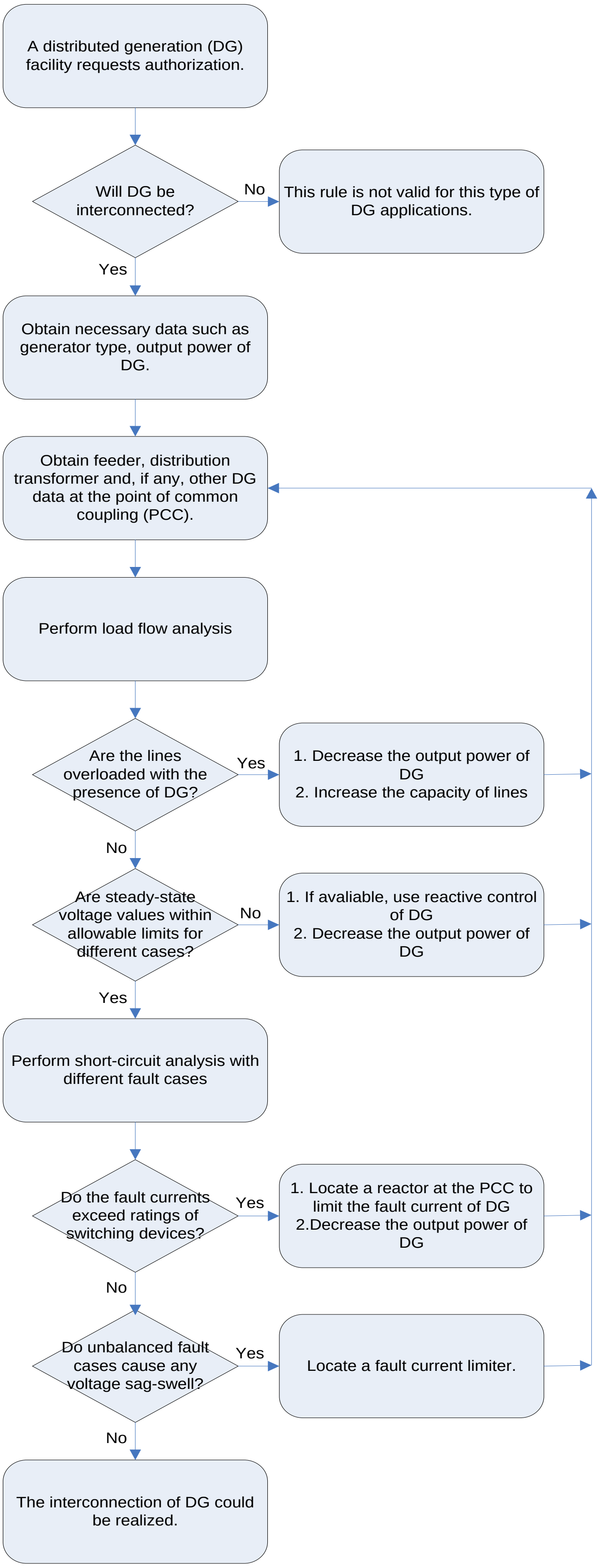

Figure 53 Flow chart for the authorization procedure

The proposed authorization procedure has been prepared as a flow chart and could be seen in Figure 53. In “Are steady-state voltage values within allowable limits for different cases?” step, the different cases include the maximum and minimum demand cases with and without DG facility interconnected. In “Do unbalanced fault cases cause any voltage sag-swell?” step, the unbalanced faults in voltage sag-swell analysis are L-G, L-L-G or L-L faults.

Among the conducted technical analyses in previous parts of the study, transient stability and voltage stability have not been mentioned in the proposed rule. This is due to the actuation time of the protection system is high and the value of inertia constants of generators used in DG applications is low. Therefore, in case of short-circuits, rotating machines will accelerate and the protection system of the DG facility will disconnect the DG unit from the network. Similarly, voltage is not listed in the rule, since voltage stability determines the amount of load that could be connected at a specific bus.

CHAPTER 4

ECONOMIC COMPARISON OF TWO INTERCONNECTION ALTERNATIVES

4.1 Introduction

DG investors have to obtain electricity generation licenses. Investors, who want to install any electricity generation facility greater than 500 kW, should get generation license given by Turkish Energy Market Regulatory Authority (EMRA). EMRA has been established to control and arrange the energy markets in Turkey to provide sufficient electricity, natural gas, petroleum and liquefied petroleum gas (LPG) of good quality to consumers at low costs in a reliable and environmental manner [55].

In order to get a license, investors should apply to EMRA with necessary information such as place, owner, energy resource, power rating and expected annual energy generation of the plant. According to the present regulations, it is possible for the distributed generators excluding wind turbines to be connected to the utility at either distribution feeders or the distribution busbar of the 154/36 kV substations [57]. In the electricity network regulations, it is ruled that for DG facilities with power rating smaller than 10 MW, the distribution system authority in Turkey will not reserve a separate line and such facilities could be connected at MV feeders [56]. However, in 2005, Turkish distribution system authority stated that every distribution generation facility should be connected at the distribution busbar of the 154/36 kV substation with a separate line. But after some changes in the related law in 2008, the above statement has been revised. Also, the wind regulation states that the wind generation facilities should be connected to utility at the distribution busbar of 154/36 kV substation and the amount of connection will not exceed 5% of the short-circuit MVA of the busbar [58].

Present situation for the licensing of DG facilities shows that there is a need of a rule in which the relevant steps to be checked are defined for the connection of DG facilities to the utility. This rule will help the investors, directors and engineers for proper installation of DG facilities. The proposed methodology in the previous chapter can be a satisfactory alternative to be used as a rule. In that methodology, the relevant analyses to be conducted for permission of connection had been listed.

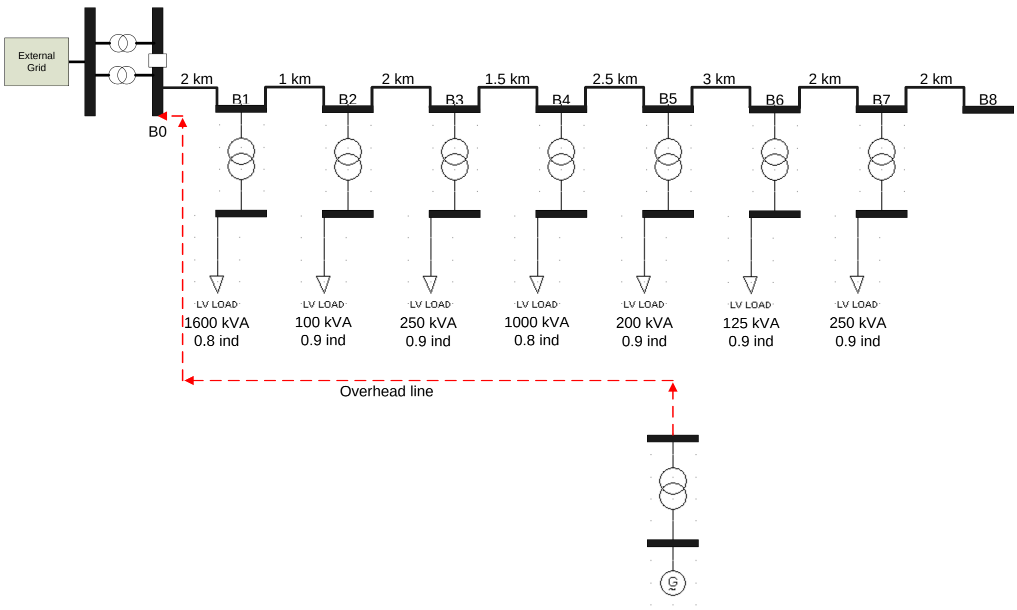

Figure 54 Connection of generation facility according to EMRA regulations

In the following parts of this chapter, the comparison of costs of different connection options will be done. This comparison will help in understanding the benefits of permitting the connection of DG facilities of all possible power ratings at distribution system level without installing separate lines after the analyses in the proposed methodology are conducted. Different possible connection alternatives include the separate line alternative in which the generation facility is connected at the distribution busbar of the 154/36 kV substation and the power is carried through a separate line, as seen in Figure 54 and distribution connection alternative in which the facility is connected to the utility at the convenient bus of the distribution system, as seen in Figure 55.

In order to perform a cost analysis, it is necessary to know about the parts of the distribution system. There are different payments in each part of the distribution system. In following studies, the parts of the distribution system will be explained briefly. Later, the payments needed for the installation of each part will be listed. Finally, the cost of installing a small hydropower plant and a photovoltaic facility will be analyzed by considering the two alternatives given in Figure 54 and Figure 55.

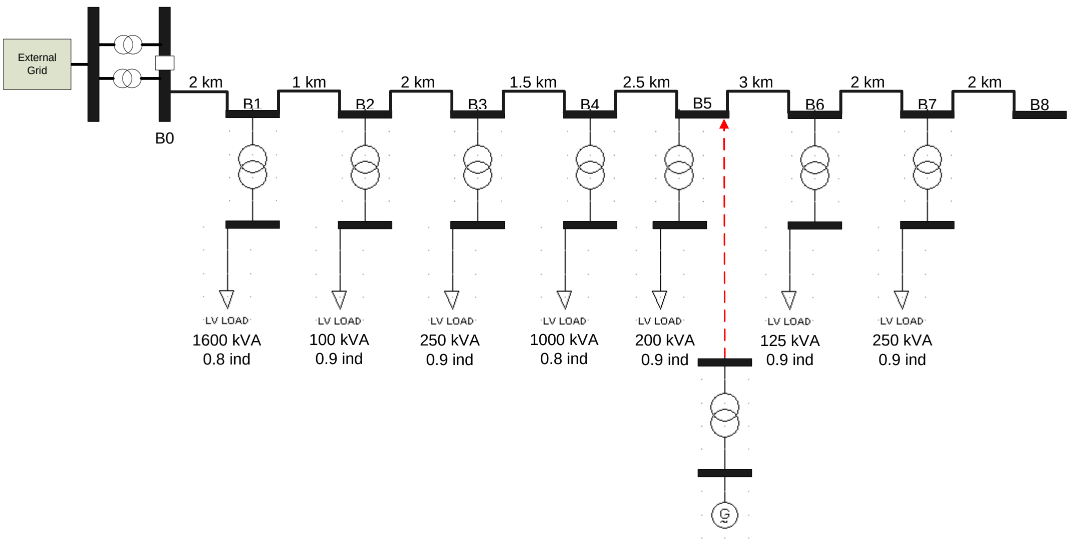

Figure 55 Connection of generation facility at distribution level

4.2 Parts of the Distribution System

By a power system, it is aimed to produce power at central power stations and to deliver generated power to end-users in a ready-to-use form at where the end-users are. The mission of a power system is to:

- Cover all the necessary territory to reach all of the end-users
- Have sufficient capacity to meet the peak demands of the end-users
- Provide highly reliable power supply
- Provide quality of power, including voltage quality

The traditional power system is composed of central power plants, transmission system, distribution system and end-users. In a traditional power system, each level is fed by the one which is closer to the generation facilities. The nominal voltage level and the average capacity of equipment decrease as one move from generation to end-user. The total capacity of each level increases as moving from generation to distribution level.

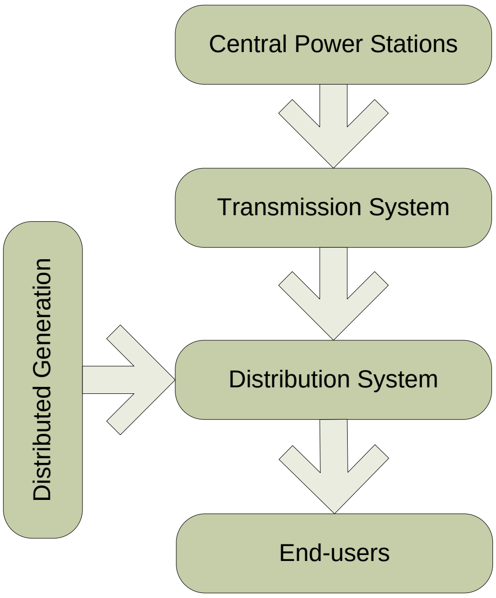

Figure 56 Parts of modern power system

However, the presence of distributed generators changes the traditional way, as seen in Figure 56. In the modern power system, the uni-directional power flow in distribution system is replaced by bi-directional power flow with the presence of distributed generators. This situation requires some additional analyses for the design of distribution system with the new approach. In this part of the study, the parts of the distribution system will be explained in detail.

Distribution systems are MV and LV level equipment that are used to supply power to the end-users. Since the end-users are dispersed throughout the territory, distribution systems cover all the customers’ places at a medium and low voltage levels in a wide area range.

A distribution system consists of medium voltage feeder system, distribution transformers and LV equipment.

4.2.1 Medium-Voltage Feeders

Feeders are current carrying conductors that route from the substation to feeder’s service area. Feeders are, typically, overhead distribution lines mounted on poles or underground buried or ducted cable sets. Feeders operate at primary distribution voltage level. The common primary distribution voltage level is 34.5 kV in Turkish power system. There are some systems where 6.3 kV, 10.5 kV and 15 kV are primary distribution voltages. It is aimed to upgrade all primary distribution equipment to 34.5 kV rating. A feeder could distribute from 2 MVA up to 30 MVA, depending on the conductor size and distribution voltage level. Feeders have excess capacity because it needs to provide back-up for the other feeders during emergency. Generally, 2-12 feeders emanate from a substation, branching into smaller ones as the feeder moves out of the substation towards the end-users.

Most of the distribution feeders are overhead construction on poles. In dense urban areas or in situations where esthetics is of concern, underground distribution feeder construction is used. Also, many times, the first several meters of the overhead primary feeder are built underground even if the system is overhead. This is done due to reliability, aesthetics and safety concerns.

4.2.2 Distribution Transformer

Distribution transformers lower the voltage from primary voltage level to utilization or end-user voltage. In Turkish power system, distribution transformers, sometimes called service transformers, is the link between 34.5 kV MV and the end-user voltage of 380 volts. Distribution transformers cover ratings from 25 kVA to 3200 kVA. These transformers may be suitable for pad mounting and pole top mounting. In overhead construction, distribution transformers are pole mounted with a rating limited by weight considerations up to 400 kVA. In underground distribution configuration, the power is supplied by padmount or vault type distribution transformers. The concept is identical to overhead construction, with the transformer and its associated equipment changed to accommodate incoming and outgoing underground lines. The efficient distance that power could be supplied with LV is 100-250 m from the distribution transformer. Therefore, it is necessary to locate at least one distribution transformer reasonably close to every end-user.

There are two basic types of distribution transformers. The first one is conventional type in which the core and the windings are enclosed in an oil filled tank which provides insulation and cooling. In dry type transformers, the core and the windings are cladded with a moisture-resistant epoxy resin and directly cooled by air.

Distribution transformers normally are not expected to be loaded up to full capacity. They are operated at 80 -90 % capacity. The remaining capacity is a margin for unexpected load increases. Tap-changing mechanisms are usually provided on HV side of the distribution transformers to change the turns ratio between the high and low voltage windings and therefore compensate the variations in primary supply voltage in order to keep the secondary voltage within allowable limits. There are normally two taps of 2.5% above and two taps 2.5% below the nominal tap [59].

4.2.3 Low-Voltage Circuits

LV circuits, also called secondary circuits, fed by the distribution transformers, route power at utilization voltage within very close proximity to the end-user, usually in an arrangement in which each transformer serves a small radial network of utilization voltage secondary and service lines, which lead directly to the meters of end-users in the immediate vicinity. It is very common to handle the layout and design of the secondary circuits through a set of standardized guidelines and tables by which engineering technicians and clerks produce work orders for LV equipment. The power is transferred to end-users from secondary lines via LV conductors called service drops. In Figure 57, LV system starting from distribution transformer is shown. At the end-users' premises, the power line first passes through an electric meter which measures and records the power used for billing purposes, then enters the main service panel. The service panel will always contain a main fuse or circuit breaker, which controls all of the electrical current entering the building at once, and a number of smaller fuses/breakers, which protect individual branch circuits. There is always a main shutoff switch to turn off all power; when circuit breakers are used this is provided by the main circuit breaker [60].

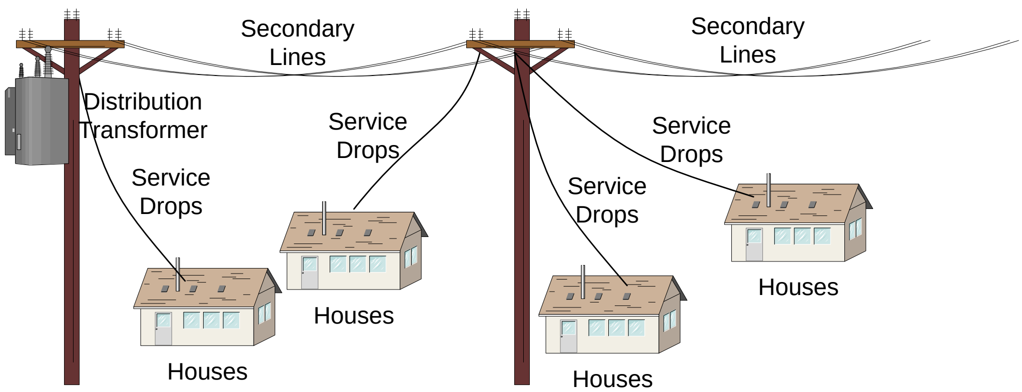

Figure 57 Pole-mounted distribution transformer, secondary lines and service drops

4.3 Distribution System Costs

A distribution system consists of medium voltage feeder system, distribution transformers and LV equipment. It could be expensive to design, build and operate a distribution system. The cost of equipment at every level of distribution system consists of two types of costs. Capital costs include the equipment and land, labor for site preparation, construction, assembly and installation, and any other costs associated with building and putting the equipment into operation. Operating costs include labor and equipment for running the system, maintenance and service, taxes and fees, as well as the value of the power wasted in electrical losses. Usually, capital cost is a one-time cost, that is, money is spent once when the system is built, whereas, operating costs are continuous or periodic.

4.3.1 Medium-Voltage Feeder System Costs

The feeder system consists of all the primary distribution lines, including three-phase trunks and their lateral extensions. These lines operate at the primary distribution voltage 34.5 kV, 15 kV, 10.5 kV, 6.3 kV and are three-phase construction. Typically, the feeder system is also considered to include sectionalizers, fuses, circuit breakers, any intertie transformers (required to connect feeders of different voltage at tie points, as, for example, 34.5 and 13.8 kV) that are installed on the feeders. MV feeder costs could vary greatly due to variations in labor, filing and permit costs among utilities, as well as differences in design standards, and terrain. Where a thick base of topsoil is present, a pole can be installed by simply auguring a hole for the pole, In areas where there is rock close below the surface, holes have to be jack-hammered or blasted, and cost goes up accordingly. It is generally less expensive to build feeders in rural areas than in suburban or urban areas.

A typical distribution feeder (AWG 1/0, 34.5 kV, three-phase) of capacity about 5-6 MVA has a recommended economic design peak loading of about 3-4 MVA, depending on losses and other costs. Underground construction of three-phase primary is more expensive, requiring buried ductwork and cable, and usually costs a range of 2-3 times more than overhead lines.

4.3.2 Distribution Transformer Costs

Distribution transformers convert primary voltage to utilization voltage. In overhead construction, a heavier pole should be used. Also, there should be hardware on the pole for locating the transformer. The mounting equipment and installation work should be considered as a cost, too. For the ground mounting construction, site cost should be considered. Site preparation and building of transformer kiosk could be a high expense. The cost of the distribution transformer includes oil containment, cooling, switches, metering, relaying and related equipment.

4.3.3 Distributed Generator Costs

Distributed generators are connecting to utility at distribution level with small amount of generations compared with the central power generation plants. The cost of the distributed generators could vary from the energy resource, i.e. hydropower plants, photovoltaics to power converter technology, i.e. SG, AG. However, there are common costs which are used for all distributed generator installation. These common costs could be listed as below:

a. Site cost: This is the cost of buying the site and preparing its equipment.
b. Generator cost: The cost of the distributed generator includes the generator, station service equipment, cable design and connection works.
c. Transformer cost: The distributed facility needs a step-up transformer for increasing the voltage level of the terminal voltage of the generator to the distribution level. The cost of the transformer includes oil spill containment, cooling, switches, metering, controls, breakers, relaying and related equipment.
d. Protection equipment: There should be protection relays having over current, over/under voltage, over/under frequency, differential and loss-of-mains protection functions for the generator and transformer. Also, the voltage and current transformers are needed to be connected to the pins of the protection relays.

e. Synchronizing Equipment: For especially SG, there should be an automatic synchronizing device for paralleling the generator with the utility.
f. Metering Equipment: This cost includes the energy metering systems of the generator for determining the energy export of the system.
g. Switchyard: This cost covers the switching devices such as circuit breakers, earth switches.

4.3.4 Maintenance and Operating Costs

After the distribution system is designed and built, it should be maintained in the manner recommended by the manufacturer. This will require periodic inspection and service, and may require repair due to damage from storms or other contingencies. In addition, taxes and fees for equipment and distribution facilities pay taxes or fees for equipment, distribution facilities like any other business property. Operating, maintenance and taxes (O&M&T) are a continuing annual expense. It is very difficult to give any generalization of O&M&T costs, partly because they vary so greatly from one region to another, but mostly because of the operational difficulties. A general rule of thumb could be offered like O&M&T costs for a power delivery system probably be between 1/8 and 1/30 of the capital cost, annually.

4.3.5 Cost of Losses

The transfer of power through conductors results in a certain amount of electrical loss due to the impedance of the conductor. Losses could be measured, priced and reduced with proper engineering. Losses could be classified according to being no-load or load-related losses. No-load losses result from the power required to establish a magnetic field and are constant regardless of loading. Load-related losses increase as the power flow increases.

4.4 Cost Analysis

Cost is the key element needed for evaluating the feasibility of DG facilities. Reliability and power quality are also essential elements to consider during evaluation but the purpose of evaluation is to select the alternative with lowest cost. An important requirement in assessing DG is to understand the cost of distribution systems and the alternative costs that might be incurred or avoided in the absence or presence of DG [62]. In the evaluation process, it is necessary to list all the relevant costs involved in installation. Costs could be categorized considering their variability and timing, as could be seen in Figure 58. The total cost could be viewed as composed of two types of costs:

a. Fixed Costs: Fixed costs are the expenses that do not vary as a function of any variable element of the plan or engineering analysis [61]. For instance, the cost of DG unit itself is a fixed cost.
b. Variable Costs: These are the expenses that vary as a function of the amount or the patterns of usage. Fuel costs could be given as an example for this kind of costs.

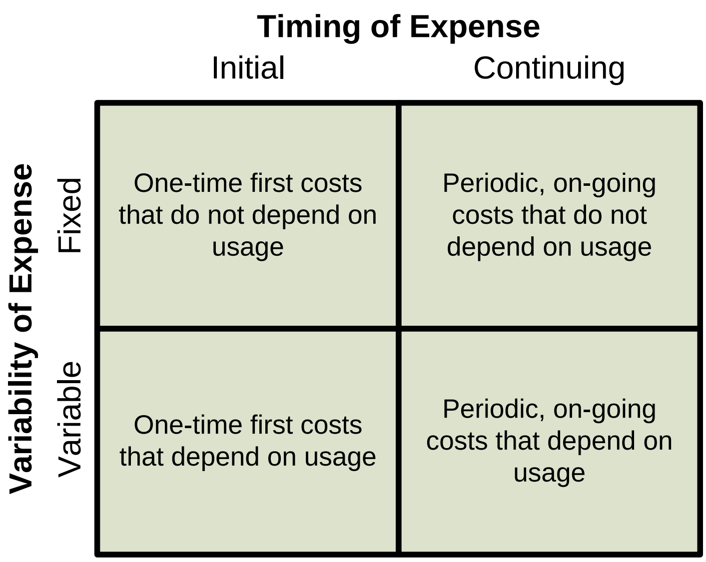

Figure 58 Categories of costs with different considerations

As another approach, it is possible to categorize the costs into two groups as:

a. Initial Costs: Initial costs are the expenses that need to be dealt before a DG unit could be used. Site preparation could be a good example for initial costs.

b. Continuing Costs: These types of costs are associated with keeping the unit available and in service. Maintenance costs could be given as an example for this kind of costs [60].

As a first step in cost analysis of installation of DG facilities, it is necessary to determine what expenses should be analyzed and which groups will be formed by these expenses. In Table 31, the expenses for the installation of DG facilities have been listed. The expenses have been divided into three main groups, MV feeder system expenses, unit transformer expenses and distributed generator unit expenses. The types of expenses have also been written in the same table according to timing and variability concern.

Table 31 Categorization of DG expenses

Medium-Voltage Feeder System Expenses		
	Design & Construction	*Fixed-Initial*
	Over head line	*Fixed-Initial*
	Poles	*Fixed-Initial*
	Operation & Maintenance	*Variable-Continuing*
Unit Transformer Expenses		
	Design & Construction	*Fixed-Initial*
	Transformer Itself	*Fixed-Initial*
	Protection System	*Fixed-Initial*
	Metering	*Fixed-Initial*
	Instrument Transformers	*Fixed-Initial*
	Site Preparation	*Fixed-Initial*
	Operation & Maintenance	*Variable-Continuing*
DG Unit Expenses		
	Design & Construction	*Fixed-Initial*
	Distributed Generation Unit Itself	*Fixed-Initial*
	Shipping & Insurance	*Fixed-Initial*
	Control System	*Fixed-Initial*
	Protection System	*Fixed-Initial*
	Auxiliary Services	*Fixed-Initial*
	Property Taxes	*Fixed-Continuing*
	Taxes for Energy Sold	*Variable-Continuing*
	Operation & Maintenance	*Variable-Continuing*

The expenses listed above are valid for any type of DG facilities. These costs should be assessed to make a financial decision. In the previous chapter, the optimum power rating for different DG facilities had been selected in order to obtain minimum total line loss. In this part of the study, two different types of DG facilities among the preselected ones will be evaluated:

- Small hydropower plant

  1800 kVA power output

  0.4 kV terminal voltage

  pf control mode of 0.9 inductive

  synchronous generator

- Photovoltaic power plant

  1400 kVA power output

  0.4 kV terminal voltage

  operated at unity power factor

  synchronous with inverter

A life-time of 20 years will be considered for both of the facilities. Both of the generators will be connected to the grid and the owners will sell of the electricity generated to the system operator. The price of the electricity changes when incentives are present. Electricity generation by photovoltaics gets more incentive than generation by hydropower plants and the amount of incentives differs country by country. For instance, in Germany, the price of photovoltaic generation is 91.4 cent/kWh [64], whereas, in Turkey, it is 50 cent/kWh [63]. For hydro power generation, the price of electricity is 15.34 cent/kWh, however, it is 10 cent/kWh in Turkey. In the following calculations, the prices in Turkey will be used.

In order to calculate the energy sold by these plants, it is necessary to obtain the generation-duration curves of these generators. In Figure 59, the daily generation-duration curve of a small hydro-power plant is shown. This type of plants has a small reservoir and generates electricity when the price of electricity is the highest. Therefore, the reservoir is filled during night and early in the morning and water is used at noon and afternoon. So, about 10 hours a day, the plant operates at full capacity. Similarly, the photovoltaic power plant’s daily generation-curve could be seen in Figure 59 [66]. Depending on the weather conditions, photovoltaics start to generate power when daylight is available.

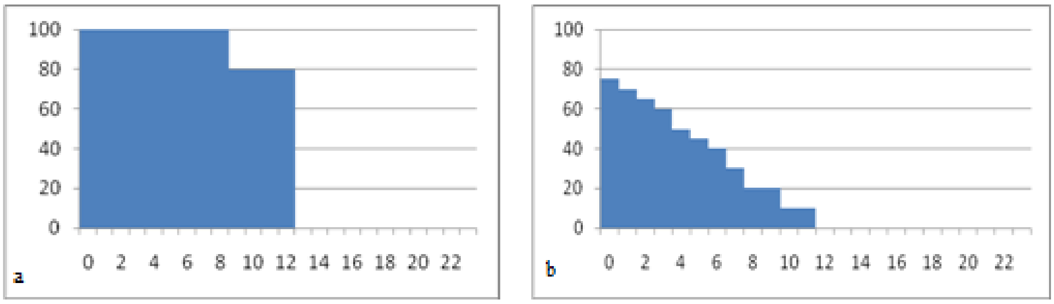

Figure 59 Daily generation curve of a) hydropower plant b) photovoltaic power plant

Considering above generation-duration curves, the annual income of power plants could be calculated as in Table 32.

Table 32 Annual incomes of hydro and photovoltaic power plants

1800 kVA-Hydro Power Plant	
Daily Electricity Generation	18144 kWh
Unit Price for Electricity	0,1 $/kWh
Daily Income	1814 $
Annual Income	662110 $
1400 kVA-Photovoltaic Power Plant	
Daily Electricity Generation	6930 kWh
Unit Price for Electricity	0,5 $/kWh
Daily Income	3465 $
Annual Income	1.264.725 $

In, the costs for the 1800 kVA-hydropower plant are listed in Table 33 [67].

Table 33 Costs of the hydro power plant in US Dollars

Fixed-Initial Costs			
	Unit Transformer Expenses		
			Costs
		Design & Construction	15000
		Transformer Itself	30000
		Protection System	10000
		Metering	3000
		Instrument Transformers	10000
		Site Preparation	18000
		Transformer Cubicles	15000
	DG Unit Expenses		
		Design & Construction	550000
		Distributed Generation Unit Itself	300000
		Shipping & Insurance	40000
		Control System	150000
		Protection System	30000
		Auxiliary Services	35000
		Generator Neutral Grounding Cubicles	30000
		Generator Leads Cubicle	40000
		Station Service - Diesel Generator	60000
		Station Service - AC&DC Distribution Boards	50000
		Station Service - Transformer	15000
		Station Service - UPS System	18000
		Station Service - AC/DC Converter System	20000
		Generator MV Cubicles	60000
Total Fixed Initial Costs			1499000
Fixed-Continuing Costs			
	DG Unit Expenses		
		Property Taxes	10000
Variable-Continuing Costs			
	Unit Transformer Expenses		
		Operation & Maintenance	4000
	DG Unit Expenses		
		Operation & Maintenance	30000
Total Variable-Continuing Costs			34000

The costs of the photovoltaic power plant are seen in Table 34[65].

Table 34 Costs of the 1400 kVA-photovoltaic power plant in US Dollars

Fixed-Initial Costs			
	Unit Transformer Expenses		
			Costs
		Design & Construction	15000
		Transformer Itself	30000
		Protection System	10000
		Metering	3000
		Instrument Transformers	10000
		Site Preparation	18000
		Transformer Cubicles	15000
	DG Unit Expenses		
		Design & Construction	1250000
		PV Array, Inverters	7980000
		Shipping & Insurance	300000
		Control System	150000
		Protection System	80000
		Auxiliary Services	10000
Total Fixed Initial Costs			9871000
Fixed-Continuing Costs			
	DG Unit Expenses		
		Property Taxes	15000
Variable-Continuing Costs			
	Unit Transformer Expenses		
		Operation & Maintenance	4000
	DG Unit Expenses		
		Operation & Maintenance	45000
Total Variable-Continuing Costs			49000

Table 35 Costs of the 9 km-feeder system in US Dollars

Fixed-Initial Costs			
	Medium-Voltage Feeder System Expenses		
			Costs
		Design & Construction	4.000
		Over head line	5.904
		Poles	135.000
Total Fixed Initial Costs			144.904
Variable-Continuing Costs			
	Medium-Voltage Feeder System Expenses		
		Operation & Maintenance	5000

Depending on the interconnection point of DG facility, a MV feeder system could be needed to be installed. If the hydropower plant or the photovoltaic power plant at Bus 5 will be connected to MV busbar of the substation, a 9-km MV feeder with poles will be constructed by the owner of the plants. The cost of the feeder system should be evaluated with the initial costs, as well. Below, in Table 35, the costs of a 9-km feeder system are listed [68].

4.4.1 Present Worth Analysis

Present worth analysis is a method of measuring and comparing costs and savings that occur at different times on a consistent and equitable basis for decision-making. The details of present worth analysis could be found in Appendix B. This analysis is based on the present worth factor. Present worth factor represents the value of money some years from now in today's terms. In above studies, the costs and the income of the hydropower and photovoltaic power plants have been listed. Using these data, it is possible to make a decision for investment using present worth analysis. After that, same analyses will be conducted considering the cost of feeder system, which should be constructed.

Table 36 Comparison of yearly expenses and income of hydropower plant in US Dollars

Year	Fixed Costs	O&M	Income	PW Factor	Discounted Costs (Fixed+O&M)	Discounted Income
0	1499000	34000	662110	1.0000	1533000	662110
1	10000	34000	662110	0.8690	38236	575374
2	10000	34000	662110	0.7552	33227	500000
3	10000	34000	662110	0.6562	28874	434500
4	10000	34000	662110	0.5703	25092	377580
5	10000	40000	662110	0.4956	24778	328117
6	10000	40000	662110	0.4306	21532	285134
7	10000	40000	662110	0.3742	18711	247781
8	10000	40000	662110	0.3252	16260	215322
9	10000	40000	662110	0.2826	14130	187115
10	10000	47000	662110	0.2456	13998	162603
11	10000	47000	662110	0.2134	12164	141302
12	10000	47000	662110	0.1855	10571	122791
13	10000	47000	662110	0.1612	9186	106706
14	10000	47000	662110	0.1400	7983	92727
15	10000	54000	662110	0.1217	7789	80580
16	10000	54000	662110	0.1058	6769	70024
17	10000	54000	662110	0.0919	5882	60851
18	10000	54000	662110	0.0799	5111	52879
19	10000	54000	662110	0.0694	4442	45952
Total	1689000	875000	13242200		1837736	4749447

In present worth analyses, inflation rate of 6 % and interest rate of 9 % have been used. In Table 36, the present worth analysis of the hydropower plant, whose costs and income have been listed above, has been listed. This case covers the connection of the hydropower plant at Bus 5 to the utility. As could be seen, the discounted income is much greater than the discounted costs. The capital investment of the hydro power plant will be paid off after 4 years.

However, when the cost of the feeder is included in the present worth analysis, it is seen that the time for the investment to be paid off is about 5 years. The cost of feeder system has decreased the profitability of the facility investment.

Table 37 Comparison of yearly expenses and income of hydropower plant with feeder system included in US Dollars

Year	Fixed Costs	O&M	Income	PW Factor	Discounted Costs (Fixed+O&M)	Discounted Income
0	1643904	34000	662110	1.0000	1677904	662110
1	10000	34000	662110	0.8690	38236	575374
2	10000	34000	662110	0.7552	33227	500000
3	10000	34000	662110	0.6562	28874	434500
4	10000	34000	662110	0.5703	25092	377580
5	10000	40000	662110	0.4956	24778	328117
6	10000	40000	662110	0.4306	21532	285134
7	10000	40000	662110	0.3742	18711	247781
8	10000	40000	662110	0.3252	16260	215322
9	10000	40000	662110	0.2826	14130	187115
10	10000	47000	662110	0.2456	13998	162603
11	10000	47000	662110	0.2134	12164	141302
12	10000	47000	662110	0.1855	10571	122791
13	10000	47000	662110	0.1612	9186	106706
14	10000	47000	662110	0.1400	7983	92727
15	10000	54000	662110	0.1217	7789	80580
16	10000	54000	662110	0.1058	6769	70024
17	10000	54000	662110	0.0919	5882	60851
18	10000	54000	662110	0.0799	5111	52879
19	10000	54000	662110	0.0694	4442	45952
Total	1833904	875000	13242200		1982640	4749447

Similarly, in Table 38, the present worth analysis of photovoltaic power plant, which will be connected to the grid at Bus 5, could be seen. The analysis shows that the investment of such a facility will not make a profit, even a huge deficit the investor will get.

Table 38 Comparison of yearly expenses and income of photovoltaic power plant in US Dollars

Year	**Fixed Costs**	**O&M**	**Income**	**PW Factor**	**Discounted Costs (Fixed+O&M)**	**Discounted Income**
0	9871000	49000	1264725	1	9920000	1264725
1	15000	49000	1264725	1	55616	1099046
2	15000	49000	1264725	1	48330	955071
3	15000	49000	1264725	1	41999	829957
4	15000	49000	1264725	1	36497	721232
5	15000	56000	1264725	0	35185	626751
6	15000	56000	1264725	0	30576	544647
7	15000	56000	1264725	0	26570	473298
8	15000	56000	1264725	0	23090	411296
9	15000	56000	1264725	0	20065	357416
10	15000	63000	1264725	0	19155	310595
11	15000	63000	1264725	0	16646	269907
12	15000	63000	1264725	0	14465	234549
13	15000	63000	1264725	0	12570	203823
14	15000	63000	1264725	0	10924	177122
15	15000	71000	1264725	0	10466	153919
16	15000	71000	1264725	0	9095	133756
17	15000	71000	1264725	0	7904	116234
18	15000	71000	1264725	0	6868	101007
19	15000	71000	1264725	0	5969	87775
Total	10156000	1195000	25294500		10351992	9072125

Since the investor will lose money for the photovoltaic power plant investment, it is not necessary to investigate the case where DG facility will be connected to the utility at distribution busbar of the 154/36 kV substation. But, in Table 39, the present worth analysis of the photovoltaic power plant and the 9 km-36 kV feeder system could be found. The presence of feeder system expense makes the situation worse. However, when compared with the cost of the photovoltaic plant, the cost of the feeder system is nearly negligible.

Table 39 Comparison of yearly expenses and income of photovoltaic power plant with feeder system included in US Dollars

Year	Fixed Costs	O&M	Income	PW Factor	Discounted Costs (Fixed+O&M)	Discounted Income
0	10015904	54000	1264725	1	10069904	1264725
1	15000	54000	1264725	1	59961	1099046
2	15000	54000	1264725	1	52106	955071
3	15000	54000	1264725	1	45280	829957
4	15000	54000	1264725	1	39349	721232
5	15000	65000	1264725	0	39645	626751
6	15000	65000	1264725	0	34452	544647
7	15000	65000	1264725	0	29938	473298
8	15000	65000	1264725	0	26016	411296
9	15000	65000	1264725	0	22608	357416
10	15000	68000	1264725	0	20383	310595
11	15000	68000	1264725	0	17713	269907
12	15000	68000	1264725	0	15393	234549
13	15000	68000	1264725	0	13376	203823
14	15000	68000	1264725	0	11624	177122
15	15000	75000	1264725	0	10953	153919
16	15000	75000	1264725	0	9518	133756
17	15000	75000	1264725	0	8271	116234
18	15000	75000	1264725	0	7188	101007
19	15000	75000	1264725	0	6246	87775
Total	10300904	1310000	25294500		10539926	9072125

4.4.2 Loss Reduction Impact of Distribution Generation Facilities

The power ratings of the power plants had been chosen so that total MV line loss is minimum. It is possible that the owner of these power plants is the distribution company, which operates the local distribution system. By this way, the distribution company reduces the amount of power bought from the transmission system and could minimize the line losses, thus earns the money paid for the losses by the customers.

Calculation of the cost of MV line losses in presence of distributed generators requires two curves: First is the load-duration curve which gives detailed information about the load over time. Second is the generation curve in which the generation characteristic of the distributed generator is shown. Using these two curves, the amount of energy losses in the sample distribution system could be calculated. By pricing the total energy losses with and without distributed generator, the economical benefit that distributed generators bring could be expressed in monetary values.

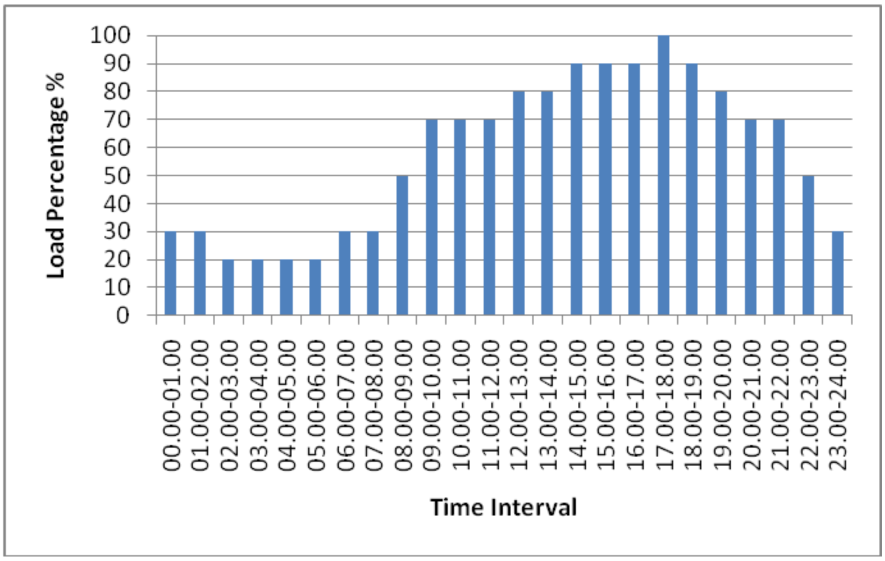

Figure 60 Load curve of a residential consumer

In Figure 60, a typical day load curve for a residential consumer in a piecewise percentage manner could be seen [59]. When there is no DG facility connected to the utility, the total MV line loss will change according to the characteristic of the loads.

At full-load, a total loss of 24 kW occurs. Then, the annual energy line loss considering load curve of costumers is

$$24 \text{ x } 365 \text{ x } (1 \text{ x } (1.0)^2 + 4 \text{ x } (0.9)^2 + 3 \text{ x } (0.8)^2 + 5 \text{ x } (0.7)^2 + 2 \text{ x } (0.5)^2 + 5 \text{ x } (0.3)^2 + 4 \text{ x } (0.2)^2)$$

$$= 85147{,}23 \text{ kWh/year}$$

When DG facilities supply power to the utility, depending on the location of the connection point, the total line losses will drop. In order to evaluate the decrease in total line losses in a day not only the load curve of the loads fed by MV feeder is needed but also generation curve of DG facility. In Figure 61, piecewise percentage generation curve of the hydropower plant could be found. Generally, these types of hydropower plants are operated at full-load when the price of electricity is maximum and stopped at times with minimum electricity price for filling the reservoir.

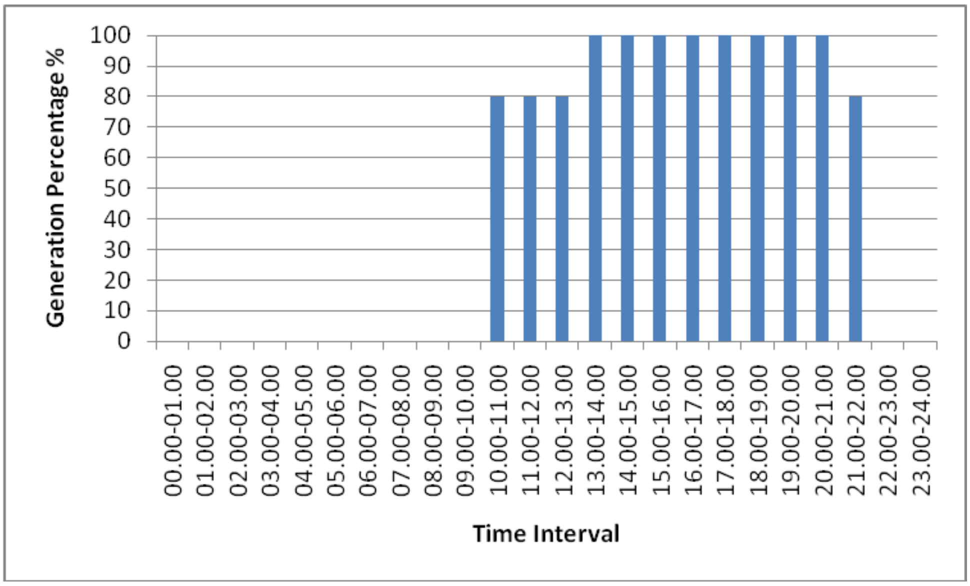

Figure 61 Generation curve of hydropower plant

In Table 40, the load and the generation percentage at each hour of the day is listed. With these load and generation conditions, the amount of total line losses at each hour has been listed. In presence of the hydropower plant, the daily total line loss is 96.2 kWh. So, the annual total line loss is 35113 kWh. As a result, it could be mentioned that the presence of DG in distribution system has dropped the total MV line losses to 41 % of the case without DG.

Price of loss is far more than the price of electricity sold to the end-users. The cost of loss is evaluated with its indirect effects. Electricity is dissipated in lines as heat instead of being used in industrial applications. So, the price of costs is 10-12 fold the price of electricity sold to end-users. Considering this effect, the drop in loss of 50034.23 kWh due to the presence of hydropower plant brings 100000 $ in a year.

Table 40 Evaluation of impact of DG on total line losses in hour-by-hour basis

Hours	Load %	DG Generation %	Total MV Line Loss (kWh)
00.00-01.00	30	0	2.2
01.00-02.00	30	0	2.2
02.00-03.00	20	0	0.9
03.00-04.00	20	0	0.9
04.00-05.00	20	0	0.9
05.00-06.00	20	0	0.9
06.00-07.00	30	0	2.2
07.00-08.00	30	0	2.2
08.00-09.00	50	0	6.3
09.00-10.00	70	0	12.8
10.00-11.00	70	80	3.1
11.00-12.00	70	80	3.1
12.00-13.00	80	80	4.2
13.00-14.00	80	100	4.6
14.00-15.00	90	100	5.6
15.00-16.00	90	100	5.6
16.00-17.00	90	100	5.6
17.00-18.00	100	100	6.9
18.00-19.00	90	100	5.6
19.00-20.00	80	100	4.6
20.00-21.00	70	100	4.2
21.00-22.00	70	80	3.1
22.00-23.00	50	0	6.3
23.00-24.00	30	0	2.2
Daily Total			96.2

4.5 Results

In this part of the study, the results of this chapter will be explained. This chapter has covered the parts and costs of the distribution system including DG, the economic analysis of two different interconnection alternatives.

Considering the costs of a hydropower plant, the highest cost is the design and construction cost which is the 36 % of the total cost, as seen in Figure 62. The generator and turbine set is 20 % of the total cost. Station service costs involve diesel generator, transformer, UPS system, AC/DC converter system and AC&DC distribution boards. Considering these costs and the present price of electricity, the investment on this hydropower plant will be paid off in 4-5 years. For a 20 year-lifetime, this investment will be very profitable.

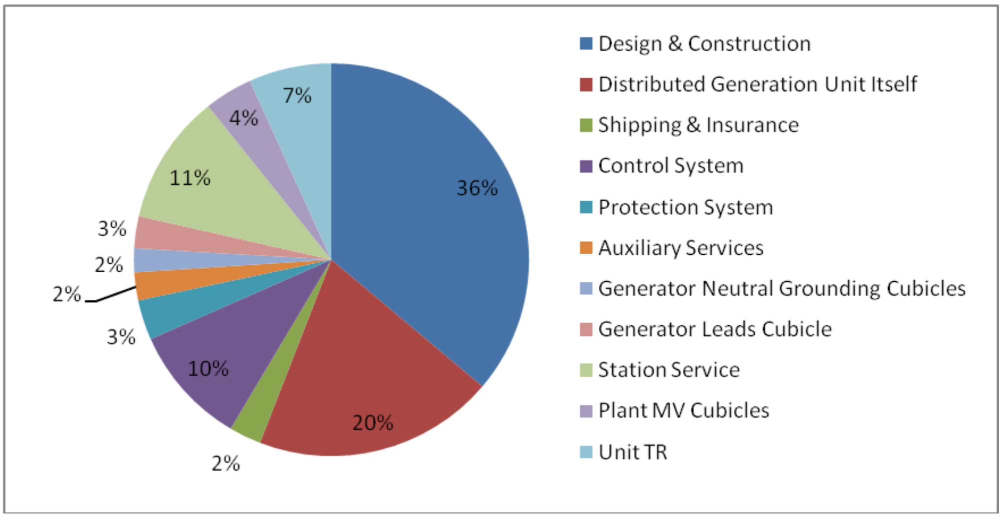

Figure 62 Percentage distribution of costs of a 1800-kVA hydropower plant

In Figure 63, the percentage costs of 1400-kVA photovoltaic power plant could be seen. The costs of PV array and inverters are so high that the other plant costs are nearly negligible. The present situation in photovoltaics show that although there is no fuel cost and the price of photovoltaic energy is increased with incentives, photovoltaic investment will be very expensive compared with the fossil energy generation. It seems that photovoltaic investors should wait for price drops in photovoltaic arrays and inverters.

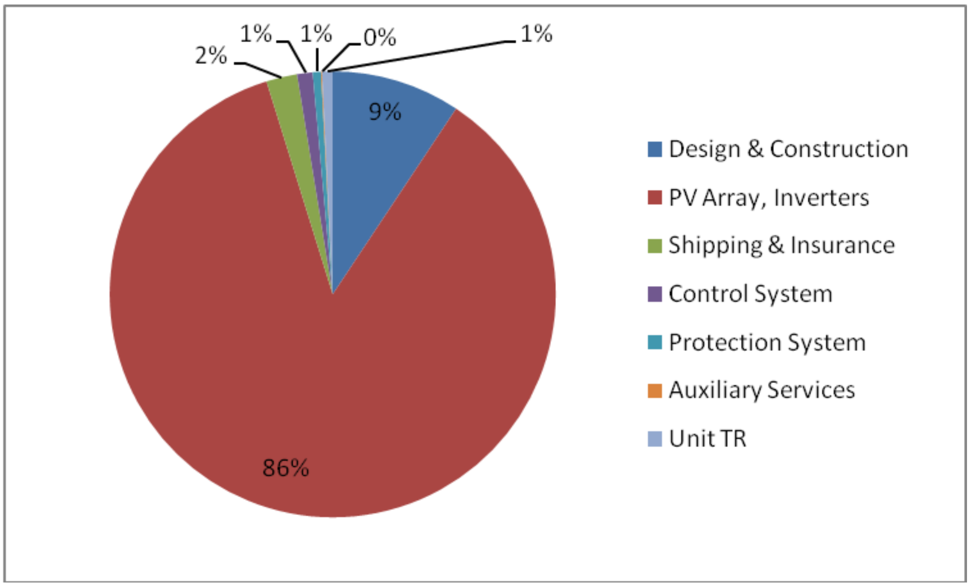

Figure 63 Percentage distribution of costs of a 1400-kVA photovoltaic plant

In coming years, the incentives for renewable energy resources are expected to increase. Also, especially, the price of photovoltaic array is expected to drop sharply and the efficiency of photovoltaic arrays is being tried to be increased. Therefore, the investment on renewable energy resources will be more profitable in future.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusions

In this thesis, an economic justification of a proposed method for the interconnection of DG at 36 kV feeder level, which has been obtained by investigating the technical and operational impacts of DG on distribution system, is presented. In this part of the study, the conclusions drawn from different concerns that have been investigated are explained.

Concerning the technical impacts of DG on distribution system, the conclusions below are drawn:

- Considering all of the technical analyses, it has been understood that different generator options used in DG applications show different characteristics in normal operation and against disturbances. This requires collecting the data of type and capacity of the generator and location and equipment of the DG facility and modeling each DG with a distinct model.
- The analyses have shown that line loss and line loading reduction could be achieved by proper sizing and location of DG application. Therefore, DG could be used for line loss and loading reduction, thus, for deferral of investments, especially, by distribution companies. In some DG applications, it is possible to decrease the line loading to the half of the no DG case.

- Among the generator options used in DG applications, SG and power electronic interfaced facilities could be utilized for Voltage/VAr control in distribution system.
- In presence of high penetration of DG, steady-state voltage values could exceed the allowable limits for distribution system due to the reverse power flow towards the utility when maximum DG and minimum load case occurs.
- The analyses have shown that presence of DG in distribution system increases the amount of short-circuit current flowing through the faulted area. This requires checking whether the ratings of the switching devices are exceeded or not as a new DG facility is connected to the network.

The conclusions below are drawn as the operational impacts of DG are concerned:

- The analysis on determination of operating reserve for wind generation has shown that the geographical distribution of wind turbines decreases the required reserve up to 30 % of the case of installing all the wind capacity at a wind site.
- Gas and hydropower plants with their fast responding components are convenient to be used as backup generation against the changes in wind generation. However, the property and the take-or-pay agreements of most of the gas power plants in Turkish power system limit the usage of these plants for backup purpose. When hydropower plants are analyzed in detail, it is seen that hydropower plants' responses against the fluctuations in wind power are fast enough after comparing the rate of change of generation in wind power and the response times of hydropower components, such as power controller, governor and turbine.
- In the present structure of Turkish power system, there is a secondary controller which sends target generation points to each plants contributing to frequency control. The addition of wind power plants could require defining, designing and implementing a wind secondary controller, which receives the output power of each wind plants and sends the target generation to the hydropower plants allocated for this purpose.

- Some of the largest hydropower plants in Turkey should be operated as backup generation for the wind turbines due to the variety in the output power of wind turbines. For this purpose, these hydropower plants should be kept as a property of the state despite the trend of the liberalization in electricity market, that is, they should not be privatized.

Concerning the rule, protection and interconnection requirements prepared for the distribution authority, the following conclusions could be drawn:

- The authorization of the interconnection of DG at the 36 kV feeders could be given after conducting the analyses including line loading, steady-state voltage variation, short-circuit contribution and power quality. With these analyses, the safety and quality of the power supply is checked against the penetration of DG in distribution system.
- The conventional protection philosophy of the power system has been designed for one-way power flow. However, with the presence of DG, a new protection philosophy in the distribution system is required, which operates properly in case of bi-directional power flow.
- Transient stability analysis for the interconnection of DG could be skipped because DG units will accelerate after a short-circuit and this acceleration will be cut by the protection system immediately. Also, voltage stability is not a requirement for interconnection since it is related with the incremental loading capacity of a specific bus.

The conclusions listed below have been drawn by concerning the economic analysis done for comparing two interconnection alternatives for the hydropower and photovoltaic power plant:

- The economic analyses have shown that with the permission of the interconnection of DG at 36 kV the investors of small hydropower plants will wait 1 year shorter for starting to get profit.
- The price of electricity generated by photovoltaic power plants is very low considering the investment cost of photovoltaic power plants. With this amount of incentives, it is not possible to get profit from these facilities.

5.2 Future Works

The presence of DG in distribution systems is a very popular issue that is investigated by many academicians and researchers all over the world. Especially, that renewable energy resources could be exploited via DG makes the issue more important. Therefore, there are many issues which are not under the scope of this study but could be nice topics for future studies. Following topics could be studied in future works:

a. <u>Interconnection of DG at LV distribution system</u>: Many small house applications of DG such as combined heat and power, photovoltaics will be realized in coming years. The technical impacts of this situation on power system, interconnection and protection requirements, necessary hardware and control system and protection coordination could be investigated.

b. <u>Reactive power control of DG applications for voltage control</u>: Some DG applications use synchronous and power converter technologies which are capable of supplying reactive power to the power system. This feature of DG facilities could be used for voltage control in distribution system, thus, improving power quality.

c. <u>The new liberalized electricity market in Turkey in presence of DG</u>: The role of DG in restructuring the electricity market in Turkey and the necessary incentive regulations needed to encourage DG investments and the effects of electricity prices on DG could be studies.

d. <u>Operation and dispatch of the power system in case of high penetration of DG</u>: It is expected that the penetration of DG in power system will be very high in the next decade. Therefore, the dispatch of generating units in the distribution system should be studied.

e. <u>Modeling Turkish power system with all types of power plants and all types of renewable energy resources</u>: The impact of all renewable resources on the frequency control could be evaluated by preparing a power system model with conventional power plants such as nuclear, thermal, gas and hydro power plants, renewable and distributed power plants such as solar, small hydro, wind power plants with the load and secondary controllers.

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APPENDIX A

TRANSFORMER CONNECTIONS

Five transformer connections are widely used to connect a DG unit to the utility. The choice of connection affects the magnitude of over-voltages after a single-phase fault and the magnitude of the fault current supplied from the substation [23]. There is no universally accepted best solution for the transformer connection selection [69].

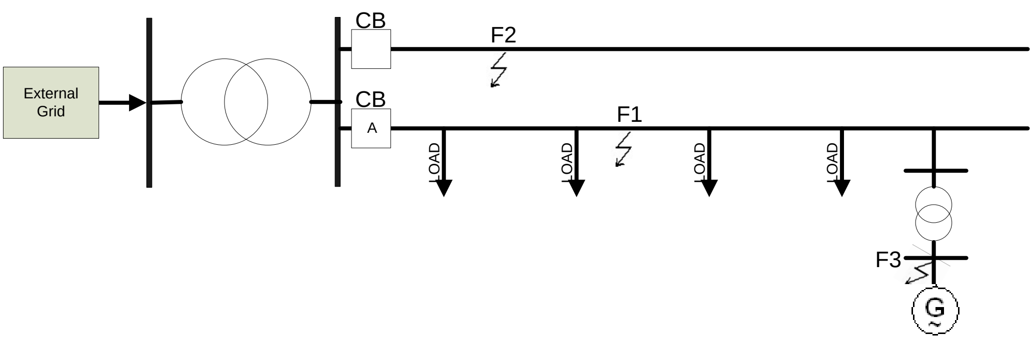

Figure A.1 Sample distribution system for transformer connections

In Table A.1, the possible connection alternatives and the pros and cons of the selection are listed. The faults mentioned in Table A.1, could be seen in Figure A.1.

Table A.1 Transformer connection alternatives

HV Side	LV Side	Advantages	Problems
Delta	Delta	Provide no ground fault backfeed for fault at F1 & F2. No ground current from CB A for a fault at F3.	Could supply the feeder circuit from an ungrounded source after CB A trips causing overvoltage.
Delta	Wye-Grounded		
Wye-Ungrounded	Delta		
Wye-Grounded	Delta	No ground current from CB A for faults at F3. NO over-voltage for ground fault at F1.	Provides an unwanted ground current for supply circuit faults at F1 and F2.
Wye-Grounded	Wye-Grounded	No over-voltage for ground fault at F1.	Allows source feeder relaying at A to respond to a secondary ground fault at F3.

Each utility will have established their preferences with regards to DG connection based on their best practice guidelines and experience. Table A.2 is the preferred configurations for a DG unit step-up transformer for the Hydro One distribution utility [70].

Table A.2 Different selections of Hydro One for transformers of DG units

System Voltage (kV) – Secondary	Generation Size	Preferred Interface Transformer High voltage side : Low voltage side (HVS:LVS)
27.6 kV	1 -2 MW	Gnd-wye : Delta Delta : Gnd-wye Gnd-wye : Gnd-wye
27.6/12/8 kV	200 kW – 1 MW	Gnd-wye : Gnd-wye Gnd-wye : Delta Delta : Gnd-wye
27.6/12/8/4 kV	50 kW – 200 kW	Gnd-wye : Gnd-wye
27.6/12/8/4 kV	10 kW – 50 kW	Gnd-wye : Gnd-wye

A.1 Delta-Delta, Delta-Wye (Grounded) and Wye (Ungrounded)-Delta Connections

The main concern with an ungrounded primary winding of the transformer is that after CB A is tripped for a ground fault at F1, the multi-grounded system is ungrounded subjecting the Line-to-Neutral (L-N) rated transformers on the unfaulted phases to an over-voltage that will be close to L-L. Many utilities use ungrounded connections only if a 200% or more overload on the generator occurs when CB A trips. During ground faults, this overload level will not allow the voltage on the unfaulted phases to rise higher than normal voltage levels.

A.2 Wye (Grounded)-Delta Connections

The main disadvantage of this connection is that an unwanted ground current is provided for a fault like F1. Even when DG facility's circuit breaker is open, the ground fault current will still be provided to the utility if DG facility transformer remains connected. In addition, the unbalanced load current on the system splits between the substation and DG transformer neutrals. This could reduce the load-carrying capabilities of the transformer. This type of connection is used for large generators connected to utility at transmission level, but presents some problems in 4-wire distribution system.

A.3 Wye (Grounded)-Wye (Grounded) Connections

This type of connection provides unwanted ground current for utility feeder faults. It also allows sensitively-set ground feeder relays at the substation to respond to ground fault on the secondary of DG transformer.

A.4 Conclusion

As seen above, all connection alternatives have advantages and disadvantages which should be evaluated by the utility. The choices of the transformer connection have impact on the connection protection requirements.

APPENDIX B

PRESENT WORTH ANALYSIS

Present worth analysis is a technique for comparing two alternative actions with different cash flows to determine which alternative has the lowest cost over time. This analysis involves translating future cash flow streams into a single present lump sum called the present worth or present value. This technique relies on the concept of the time value of money that money earned in the future is worth less than money earned today, because it could be used today by investing or spending for an immediate need. Future cash flows are converted to present worth amounts by present worth factor [71].

The value of money at any time in the future could be converted to its present worth as [72]:

$$\text{Present worth of M} = M \times P^t \tag{1}$$

where M: amount of money

P: present worth factor

t: years ahead when M is earned/spent

Present worth analysis discounts the value of the future costs and savings just because they lie in the future. Present worth factor is simply a value that sums up all the reasons why an organization would prefer to spend money tomorrow rather than today. It could also be used for evaluating one option with different cash flows happening at different times.

When the inflation and interest rate are considered, the present worth factor is calculated as [60]:

$$P = 1 / (1 + d) = 1 / (1 + \text{interest rate\%} + \text{inflation rate \%}) \qquad (2)$$

Discount rate, d, is the rate of reduction value. It is generally, greater than the interest rate. Therefore, inflation rate is included when calculating discount rate.

In order to complete the analysis, all costs and income during the lifetime of the plant should be converted to today's values by using present worth factor and the sum of all incomes and costs will show whether the project is profitable or not.

APPENDIX C

WIND INVESTMENTS IN TURKISH POWER SYSTEM

Wind investments in Turkish power system have increased after 2000's. Below, in Table C.1, the present installations and the planned installation of wind power system have been listed.

Table C.1 List of wind generation plants planned to be in operation until 2010/I

Company	Location	Operation Date	Installed Power (MW)
Alize A.Ş.	İzmir-Çeşme	1998	1.5
Güçbirliği A.Ş.	İzmir-Çeşme	1998	7.2
Bores A.Ş.	Çanakkale-Bozcaada	2000	10.2
Sunjüt A.Ş.	İstanbul-Hadımköy	2003	1.2
Bares A.Ş.	Balıkesir-Bandırma	2006/I	30
Ertürk A.Ş.	İstanbul-Silivri	2006/II	0.85
Mare A.Ş.	İzmir-Çeşme	2007/I	39.2
Deniz A.Ş.	Manisa-Akhisar	2007/I	10.8
Anemon A.Ş.	Çanakkale-İntepe	2007/I	30.4
Doğal A.Ş.	Çanakkale-Gelibolu	2007/II	14.9
Doğal A.Ş.	Çanakkale-Gelibolu	2007/II	14.9
Deniz A.Ş. (Aksa)	Hatay-Samandağ	2008/I	30
Doğal A.Ş.	Manisa-Sayalar	2008/I	30.4
İnnores A.Ş. (Dost Enerji)	İzmir-Aliağa	2008/I	42.5
Lodos A.Ş.	İstanbul-GOP	2008/II	24
Ertürk A.Ş.	İstanbul-Çatalca	2008/II	60
Baki A.Ş.	Balıkesir-Şamlı	2008/II	90
Dares A.Ş.	Muğla-Datça	2008/II	28.8
Ezse Ltd. Şti.	Hatay-Samandağ	2008/II	35.1
Ezse Ltd. Şti.	Hatay-Samandağ	2008/II	22.5
Ayen A.Ş.	Aydın-Didim	2008/II	31.5
Kores A.Ş.	İzmir-Çeşme	2008/II	15

Table C.1 Continued

Company	Location	Operation Date	Installed Power (MW)
Alize A.Ş.	Balıkesir-Susurluk	2008/II	19
Alize A.Ş.	Balıkesir-Susurluk	2008/II	19
Rotor A.Ş.	Osmaniye-Bahçe	2009/I	135
Mazı-3 Res Elk. Ür. A.Ş.	İzmir – Çeşme	2009/I	22.5
Borasco A.Ş.	Balıkesir-Bandırma	2009/I	45
Alize A.Ş.	Tekirdağ-Şarköy	2009/I	28.8
Alize A.Ş.	Tekirdağ-Şarköy	2009/I	28.8
Alize A.Ş.	Balıkesir-Havran	2009/I	16
Alize A.Ş.	Çanakkale-Ezine	2009/I	20.8
Alize A.Ş.	Çanakkale-Ezine	2009/I	20.8
Alize A.Ş.	Manisa-Kırkağaç	2009/II	25.6
Soma A.Ş.	Manisa-Soma	2009/II	140.8
Boreas A.Ş.	Edirne-Enez	2009/II	15
Doruk A.Ş.	İzmir-Aliağa	2009/II	30
Yapısan İnş. Elk. San.Tic. A.Ş.	İzmir-Aliağa	2009/II	90
Doğal A.Ş.	İzmir-Aliağa	2010/I	30
Doğal A.Ş.	İzmir-Foça	2010/I	30
Poyraz A.Ş.	Balıkesir-Kepsut	2010/I	54.9
Bilgin Elektrik Üretim A.Ş.	Manisa-Soma	2010/I	90
Bares Elektrik Üretim A.Ş.	Balıkesir-Kepsut	2010/I	142.5
Total in Operation			1,228.05
Total in 2010/I			1,575.45