IMPACT
OF
HIGH-LEVEL DISTRIBUTED GENERATION PENETRATION
ON THE
TRANSMISSION SYSTEM TRANSIENT STABILITY

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Approval of thesis:

IMPACT OF HIGH-LEVEL DISTRIBUTED GENERATION PENETRATION ON THE TRANSMISSION SYSTEM TRANSIENT STABILITY

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ABSTRACT

IMPACT OF HIGH-LEVEL DISTRIBUTED GENERATION PENETRATION
ON THE TRANSMISSION SYSTEM TRANSIENT STABILITY

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This thesis investigates the impact of high-level penetration of distributed generation especially from the renewable energy sources on the transient stability of the transmission system.

Distributed generation is a source of electric power connected to the distribution network or on the consumer side. It is expected that distributed generation grows significantly by the increasing environmental concerns and deregulation in the market. As soon as the increasing penetration level, distributed generation starts to influence the distribution system as well as the transmission system.

To investigate the impact of distributed generation with different penetration levels on the transmission system transient stability, simulation scenarios are created and simulations are run on the basis of these scenarios by the implementation of the different distributed generation technologies to the “New England” test system. Stability indicators are observed to assess the impact on the transient stability.

Results are presented throughout the thesis and the impact of the different distributed generation technologies and the different penetration levels on the transient stability is discussed by comparing the stability indicators.

Keywords- distributed generation, transient stability, renewable generation

ÖZ

DAĞITILMIŞ ÜRETİMİN YÜKSEK SEVİYEDE YAYGINLIK ORANININ
İLETİM SİSTEMİ GEÇİCİ KARARLILIĞINA ETKİSİ

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Bu tezde, özellikle yenilenebilir enerji kaynaklarını içeren dağıtılmış üretimin (distributed generation) güç sistemlerindeki yaygınlık oran (penetration level) artışının iletim sistemi geçici hal kararlılığına etkisi incelenmiştir.

Dağıtılmış üretim sisteme orta veya düşük gerilim seviyesinden bağlanan elektrik enerjisi üretim şeklidir. Yakın gelecekte, artan çevresel kaygıların ve özel sektöre verilen teşviklerin de etkisiyle dağıtılmış üretimden üretilen elektrik enerjisinin ciddi oranda artması beklenmektedir. Bu artışla birlikte dağınık üretimin hem dağıtım hem de iletim seviyelerinde güç sistem kararlığı üzerinde etkileri gözükecektir.

Dağıtılmış üretimin, farklı yaygınlık oranlarında iletim sistemi geçici hal kararlılığı üzerindeki etkisini incelemek için benzetim senaryoları yaratılmış ve farklı dağıtılmış enerji üretim teknolojileri “New England” test sistemine bağlanarak bu senaryolara uygun olarak bilgisayar benzetimleri yapılmıştır. Sistem geçici hal kararlılığının nasıl etkilendiğini değerlendirmek için tanımlanan kararlılık belirteçlerinin değişimi gözlemlenmiştir.

Sonuçlar tez boyunca sunulmuş ve benzetim sonuçlarından elde edilen kararlılık belirteçleri kıyaslanarak, farklı dağıtılmış üretim teknolojilerinin ve farklı yaygınlık oranlarının geçici hal kararlılığı üzerindeki etkileri tartışılmıştır.

Anahtar Kelimeler- dağıtılmış üretim, geçici hal kararlılığı, yenilenebilir enerji

To My Parents and My Brother

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CHAPTER 1

INTRODUCTION

1.1 Motivation and Objectives of the Study

The rapid development of Distributed Generation (DG) is gradually reshaping the conventional power systems in the world. A number of reasons for this development exist. Primary one is the increasing concern on reducing the environmental impact of power generation which encourages the researches on power generation from renewable energy sources. Researches are focused on the increasing power generation not only from renewable energy sources but also from small generation units instead of centrally dispatched large units. Wind turbines, photovoltaics, microturbines and small hydro-plants are the most actively developing DG technologies. The focus of this study is on the generation from renewable energy sources.

Implementation of DG technologies triggers the transformation of classical power systems into more complex systems. It increases the complexity of controlling, protecting and maintaining the transmission systems as well as the distribution systems. The increasing complexity of the transmission and the distribution systems through DG technologies has technical impacts on the network. These impacts are required to be analyzed at the different operational levels respectively, transmission and distribution. The aim of this study is to investigate the impacts on transmission system.

Presently, impact of DG on the transmission system is assessed by running traditional power flow computations. It is a feasible action as long as the penetration level of DG is relatively small. However, as the penetration of DG increases, its impact on power system could be no longer neglected and it will require detailed dynamic analysis of the systems. The implementation of DG influences the dynamic performance of a power system in rotor angle (transient) stability, voltage stability and frequency stability. In this study, the focus is on the transient stability.

The main objective of this study is to investigate the impact of high-level renewable generation penetration on the transmission system transient stability. This is fulfilled by comparing the stability indicators (described in Chapter 3) of a test system for different scenarios. The scenarios are created by the implementation of different DG technologies for different penetration levels and fault durations. An assessment is brought out by observing the variation of indicators for these different simulation scenarios.

1.2 Outline of the Thesis

The thesis consists of four main chapters describing the general information about the topic and results of the study;

i. Chapter 2 briefly touches on the present power generation situation and conventional generating units. The reasons of the transformation of conventional power generation and the expected new generation era are discussed. The definition of DG is made and a general overview on different DG technologies and storage systems is given.

ii. Chapter 3 briefly describes the power system stability concept and the classification of power system stability is presented. Moreover, the indicators used to assess the impacts of different DG technologies with high penetration on power system transient stability are described in this chapter.

iii. Chapter 4 focuses on the presentation of New England (IEEE 39-bus) test system which is used as a test system in this study. System characteristics, dynamic models of centralized generators and distributed generators are given. Clarification of how distributed generators are connected to the test system is made.

iv. Chapter 5 includes the description of simulation scenarios, simulation results and discussions. The simulations which are ran to assess the impacts of penetration of DG on power system stability are depicted and discussions are made on the results. Advantages and disadvantages of the implementation of different DG technologies are tried to be obtained by the comparison of the indicators for different penetration levels and fault durations. The critical clearing time (CCT) variation of the system for different penetration levels of DG is investigated.

CHAPTER 2

DISTRIBUTED GENERATION

2.1 Current Power Generation Situation and Expected Generation Era

When electric energy began to be used in a place, electricity was supplied by generations very near to the demand, and directly installed into the distribution network [1]; in other words, electricity was supplied by the distributed generators at the beginning. Later on, increasing electricity energy demand could be met by installing the large capacity generators which are mostly near the primary energy sources.

Electricity has been supplied by the three major types of power plants since the beginning of the twentieth century, hydro, thermal (coal, oil or gas) and nuclear power plants. They mostly have high power generation capacities and are located far from the users. Installed capacity of the other generation technologies is very low at the moment. Value and percentage of worldwide installed capacity of generation technologies by 1 January 2006 is given in figure 2.1.

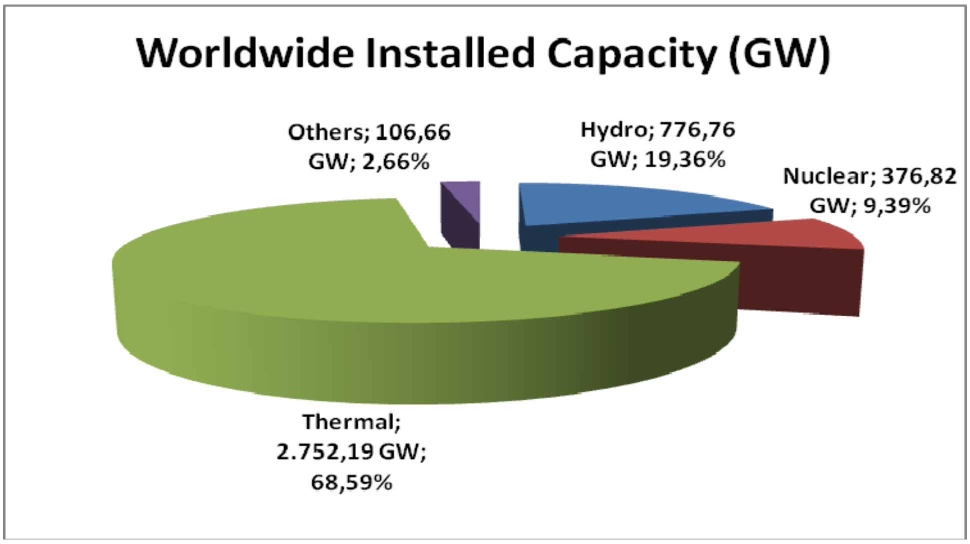

Figure 2.1: Worldwide installed electricity capacity by 1 January 2006 [2]

Power systems with centralized large generating units can be efficient for their, less generator reserve requirement and being operated with few personnel however these traditional major types of generators have inherent problems considering technological, environmental and economical aspects.

Hydro power plants use water as source. They are clean, cheap and efficient way of generating electricity. They are the most preferable type of generation but feasible projects have been substantially built in most of the developed countries. Therefore, it is not possible to meet the increased power demand by the hydro power plants in proportion to their current installed capacity percentage. They do not pollute environment in their daily operation but they destroy natural life of the constructed land and people living in the area must move out due to flooding.

Thermal power plants mostly use fossil fuels. The majority of fuels used in the plants are coal, oil and natural gases. The energy released during burning of fuel heats water and it turns into steam. Steam turbines drive an electricity generator to generate electricity. The wide ranges of generation types use thermal energy conversion. Hence, thermal power plants are the most common electricity production way in the world. Nearly 70 percent of the installed electricity capacity is produced by thermal plants [2].

Nuclear energy is a highly controversial topic due to the nuclear reactor accident risk and fallouts. Nuclear power plants generate electricity by extracting energy from atomic nuclei through nuclear fission. The extracted energy is used to heat water and produce steam which is then converted into mechanical energy to generate electricity. Although ten percent of installed capacity of electricity is supplied by the nuclear power plants at the moment, nuclear power production will decrease during coming years as the old plants are retired and are not being replaced. Several European countries have established laws to accelerate the decommissioning of existing nuclear power plants [3].

Considering reduction in gaseous emissions, more energy generation from renewable energy sources, energy efficiency, deregulation and competition in the market, high cost of transmission systems, generation closer to consumer and short construction time, it is expected that distributed generation is becoming more popular in all over the world. By 2050, the World Energy Council envisages the global energy mix will be made up of at least nine energy sources (coal, oil, gas, nuclear, hydro, biomass, wind, solar and geothermal) with none expected to have more than a 30% share of the market [4]. This will trigger the transformation of classical power system to more complicated systems.

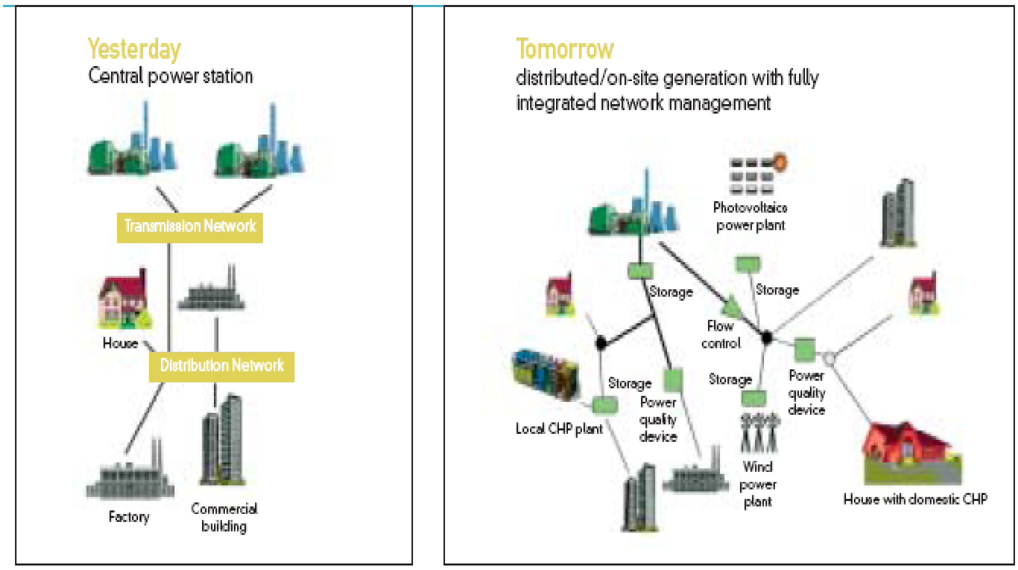

Figure 2.2: Yesterday and tomorrow of power system

2.2 What is Distributed Generation?

Many different definitions of Distributed Generation (DG) can be found. Despite DG is not a new concept for energy sector, it has started to draw attention in recent years. Hence a generally accepted definition or designation of DG is not available. In different areas, different designations and definitions are used for distributed generation. South American countries often use the term ‘Embedded Generation’, North American countries the term ‘Dispersed Generation’, some parts of Asia, the term ‘Decentralized Generation’ and in Europe the term ‘ Distributed Generation’ is applied for the same type of generation [5]. T. Ackerman and G. Andersson published a paper named, Distributed generation: a definition [5], intending both to provide general definitions of the purpose, the location, the technology and the rating of DG and to eliminate the large variations of definitions. According to this paper (the same is also accepted by European Commission), Distributed Generation can be defined as a source of electric power connected directly to the distribution network or on the consumer side of meter [4]-[5]. Distributed generation includes all of the generators connected to utility over distribution network and isolated generators (not connected to the power grid). In the some sources, distributed generation is defined as small, modular, decentralized, grid-connected or off-grid energy systems located in or near the place where energy is used [30]. In this approach, DG may be interconnected with a local utility company's distribution system or not. However in the both approaches, the definition of DG does not comprise the rating of the generator source. However, it is useful to introduce the categories of different ratings of distributed generation. The suggested categories in [5] are;

Table 2.1: Relative size of DG

Micro distributed generation:	1 Watt<5 kW
Small distributed generation:	5 kW<5 MW
Medium distributed generation:	5 MW<50 MW
Large distributed generation:	50 MW<300 MW

Distributed generation is the most promising generation type in the modern power systems. There are a lot of projects available worldwide regarding DG, which are in progress or in planning stage. While installed capacity of DG is increasing, it brings both advantages and disadvantages. Advantages can be listed as follows [1] - [6] – [7] - [8];

- Lower carbon emissions which may satisfy the customers demand for green power increasing
- Energy efficiency or rational use of energy
- Lower capital cost
- Short construction period
- Easier to find sites for smaller generators
- Generation may be sited closer to load allows available sources of energy to be used, e.g. natural gas, which is widely used as fuel for DG, is widely available in most customer load centers.
- Reduced investment in the transmission and distribution network by local generation and consumption
- Convenient local positioning reduces transmission and distribution losses
- Voltage support

- Provision of back-up power
- Allows more efficient use of heat

Disadvantages include [7]-[8];

- Islanded Operation
- Increase in short-circuit level
- Unknown effect on power quality
- Harmonic injection into the system by DG sources which use power electronic interface
- Voltage control problems
- Complication of operating problems
- Protection coordination problem

Contrary to common belief, DG does not include technologies only to generate electricity from renewable energy sources; it is a way of generating electricity from renewable and non-renewable energy sources. Renewable energy sources include [9];

- Hydro power (large and small)
- Biomass (solids, bio fuels, landfill gas, sewage treatment plant gas and biogas)
- Wind
- Solar (photovoltaic, thermal electric)
- Geothermal
- Wave and tidal energy

- Biodegradable waste.

Non-renewable energy sources are;

- Fossil Fuels (Oil, Natural Gas, Coal)
- Nuclear Fuels.

2.3 Distributed Generators

Table 2.2: Distributed generation technologies

Distributed Generation Technologies:	**Capacity**	**Utility Interface**
Microturbines	A few tens of KW to a few MW	AC to AC Converter
Conventional Fossil-Fuel Based Generators	KW's to a few hundred MW	Synchronous Generator
Combined Heat and Power (CHP) Plants	A few tens of KW's to hundreds of MW	Synchronous Generator
Small hydro-Power Plants	A few KW's to a few tens of MW	Synchronous Generator
Wind Power Plants	A few hundred W to a few MW	Asynchronous Generator
Offshore Wind Power Plants	KW's to a few hundred MW	Asynchronous Generator
Photovoltaics	A few W to hundreds of kW	DC to AC Converter
Solar Thermal Power Plants	Several hundreds kW to a few tens of MW	Synchronous Generator
Fuel Cells	A few KW's to a few tens of MW	DC to AC Converter
Geothermal Power Plants	A few hundred kW to several tens of MW	Synchronous Generator
Biomass Power Plants	A few hundred kW to a few tens of MW	Synchronous Generator
Tidal Power Plants	A few hundred kW to a few MW	Four-Quadrant Synchronous Generator
Wave Power Plants	A few hundred kW to a few MW	Four-Quadrant Synchronous Generator

There are different available technologies used as distributed generator in the modern power systems, including both generation from renewable energy sources and non-renewable sources. Their electricity generating capacities and technologies for interconnection with grid show difference. Various technologies used as DG, their generation capacities and utility interfaces are listed in table 2.2.

2.3.1 Distributed Generation from Non-Renewable Energy Sources:

2.3.1.1 Combined Heat and Power (CHP) Plants:

Combined Heat and Power (CHP) system, also known as cogeneration, is an efficient and effective way of converting fuel into electric and thermal energy [10]. The electrical power is produced by an electric generator which has a primary mover such as a steam turbine, reciprocating engine or gas turbine. CHP systems are appropriate solution for any facility that needs both electrical and thermal energy. They are the most popular type of distributed generation at the present. CHP plants technologies exist for a range of generation capacity from a few kW to hundreds of MW. CHP can be 60 to 80 percent efficient by simultaneous production of electric power and heat. They are used both as DG or CG. CHP plants are directly connected to the power systems.

2.3.1.2 Microturbines:

Microturbines are essentially very small combustion turbines, individually of the size of a refrigerator, that are often packaged in multiunit systems [3]. They are widely used as distributed generators. Their size is up to hundreds of kW. Efficiency of microturbines varies 25 to 30 percent but including to Combined and Heat Power systems, it may increase up to 80 percent.

Figure 2.4: 30 kW Microturbines [3]

Microturbines operate at high speed range from 50.000 to 120.000 rpm, depending on the output capacity of the microturbine [3]. Within the power-electronic interface, the high-frequency electrical power output is converted to DC before it is inverted back to the low-frequency AC of the grid [11].

2.3.1.3 Conventional Fossil-Fuel Based Generators:

Within the category DG, the term “Conventional Fossil-Fuel Based Generators” is used to describe small fossil-fueled power plants within a range of kWs up to a few hundred of MWs, gas turbines and reciprocating engines are most common one in this type of generation [11].

Reciprocating engines are widely used as DG. They have a wide range of output from few kW to about 10 MW and are usually fuelled by diesel or natural gas. With development of modern emissions control technology, their impact to environment is low and also they can be run using biomass-derived fuels [4].

2.3.1.4 Fuel Cells:

Fuel cells are electromechanical devices which combine hydrogen and oxygen to produce electricity. They can operate as long as fuel is provided. Fuel cells generate Direct Current (DC) power and connect to the system by DC to AC converters.

Figure 2.3: Five Unit 200 kW Fuel cells

Distributed generation applications include power units for home or auxiliary and back-up power generation units. Fuel Cells for DG applications are designed up to a few MW levels. They are very useful as electricity source in remote areas. Fuel cells have very high electrical efficiency but due to high investment cost and short life, they are not commercially preferable at the moment.

2.3.2 Distributed Generation from Renewable Energy Sources:

2.3.2.1 Photovoltaics:

Photovoltaic (PV) systems use energy from sun to generate electricity. As a clean source, demand to the PV has been increasing incrementally in the recent years. Most of the countries in the world encourage electricity production from PV systems by giving financial support to the companies. Despite that, payback of investment to build PV systems is still around 15-20 years due to high installation cost. They are competitive for remote applications (stand-alone). Such systems generally involve storage systems, and hybrid systems also include one or more auxiliary power generators to ensure continuity of supply [4]. Capability range of PV systems is from few W to hundreds of kW. PV systems produce DC power and they are connected to the utility by DC to AC converters.

2.3.2.2 Solar Thermal Power Plants:

Solar thermal power plants are also known as “Concentrated Solar Power Plants”. Solar thermal power plants do not directly convert solar energy to electric energy like photovoltaic. They use heat, which is generated by using lenses and reflectors to concentrate sun energy, to drive steam turbine and steam turbine drives an electrical generator that converts the mechanical energy into electrical energy. It is an efficient way of generating electricity from sun.

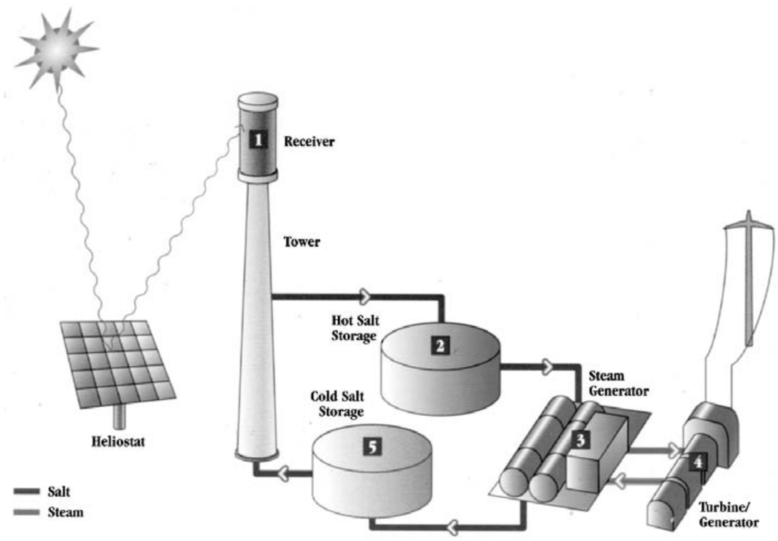

Figure 2.5: Solar thermal power plant schematic for generating electricity [12].

Solar Thermal Power Plants are used for medium to large applications from MW to hundreds of MW with a minimum size of about 5 MW. This technology is available since 1980s but it is still expensive and has intermittent nature. Studies have shown a significant solar energy potential for solar thermal power across Mediterranean region [4]. Unlike PV technology, solar thermal power plants are directly coupled to the grid.

2.3.2.3 Wind Power Plants:

Wind power plants first convert kinetic energy of wind to mechanical energy then to electrical energy. Wind energy is the most promising energy source in the 21th century. It is a clean, renewable and sustainable energy source. Growth in wind energy is significant and over 120 GW of capacity had been installed worldwide by the end of 2008 and 65 GW of this being in Europe [4]-[13].

The conversion of the mechanical power of the wind turbine into the electrical power can be accomplished either by synchronous machine or induction machine. Most wind turbines in the world use induction generator to generate AC. The speed of the induction generator may vary with the rotating force (moment, or torque) applied to it. In practice, however, the difference between the rotational speed at peak power and at idle is very small, about 1 per cent. Usually, a gearbox is used (Figure 2.6) to connect the low-speed driving shaft to the high-speed generator shaft (1200 to 1500 rpm) [11].

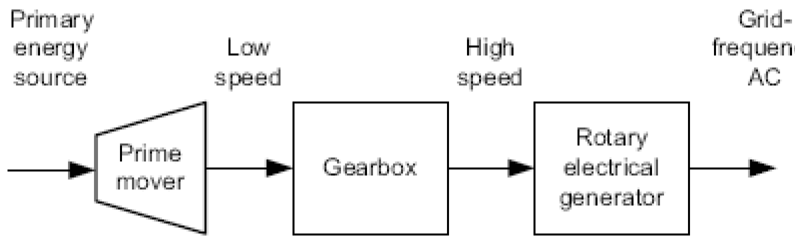

Figure 2.6: Schematic diagram of grid connected DG via gearbox [11]

2.3.2.4 Offshore Wind Power Plants:

The other important development in wind energy is offshore installation. Offshore wind energy has the potential to provide substantially amount of energy in the world and is a promising application of wind energy especially in the countries with high cost land and population.

Advantages of installation offshore to land wind farms are reduced visual impact, higher mean wind speed, reduced wind turbulence; and disadvantages include, higher capital costs, access restrictions in poor weather, requiring submarine cables and integration difficulties with distribution networks which are located in remote areas [6].

2.3.2.5 Small-scale Hydro Power Plants:

Small-scale hydro-power plants generate electricity from the movement of water from a river, a rivulet or a canal where the power house is placed. Generally, hydro power plants with a capacity up to a few tens of MW are accepted as small-scale hydro.

Small-scale hydro power plants are one of the most popular alternative energy sources nowadays, especially in remote areas. Their construction cost is low, have short construction schedule and also have minimal operational cost. In small hydro power plants, the generator is connected to the turbine so that mechanic output of the turbine is fed in to generator to produce electricity. Both synchronous or induction generators can be used in these applications.

2.3.2.6 Geothermal Power Plants:

Geothermal power plants convert the energy contained in hot rock into electricity by using water to absorb the heat from the rock and transport it to the surface of the earth [11]. In geothermal power plants steam, heat or hot water from geothermal reservoirs provide the force that drives the turbine generators, then geothermal water used is returned through an injection tube into the reservoir to be reheated [14].

Geothermal energy is a clean and renewable energy source. It is not generally affected by weather (seasonal differences may affect plant efficiency), available throughout the day and more predictable compare to wind and solar. Turkey is one of the leading countries in the world in regarding available geothermal sources. Geothermal power plants are directly connected to the system like other thermal power plants.

2.3.2.7 Tidal Power Plants:

Primary energy of tidal power plants is the movement of the huge amount of water by the gravitational forces of the sun, moon and earth. They work like hydro-electric plants but they require much bigger dams. Kinetic energy created by the movement during falling and rising of ocean tides, is captured by underwater turbines which are located at the areas with high tidal movement to produce electricity.

Contrary to wind and solar energy, tidal energy is predictable, does not have any waste, and not produce greenhouse gases, maintenance cost is minimal and once built, tidal energy is free. In view of these, they have high potential for future electricity generation.

2.3.2.8 Wave Power Plants:

Wave energy is converted to electricity by placing generators to ocean surface. The energy in waves comes from the movement of the ocean water and changing heights and speed of the swells [14]. Wave power is a renewable and environmentally friendly energy source. Although output of the wave power plants cannot be determined like PV and wind, wave conditions can be forecasted over periods of days.

Although AC rotating machines are used in tidal and wave power plants, they can be directly or indirectly coupled to the grid. If the AC power output is close to the system frequency, they are connected directly. But in some cases, generating electricity with frequency deviation from the system frequency can be more economical by reasons of intermittent primary source and they coupled to the grid by power electronic interface.

2.3.2.9 Biomass Power Plants:

Biomass includes all water- and land-based vegetation and trees, municipal biosolids (sewage), animal wastes (manures), forestry and agricultural residues, and certain types of industrial wastes [11]. It’s one of the largest renewable energy sources.

There are some technological ways to convert biomass to renewable energy sources; thermal conversion (when biomass burned, energy is released as heat), chemical conversion (converting biomass into a fuel), biochemical conversion (makes use of the enzymes of bacteria and other micro-organisms to break down biomass [15]).

Biomass is converted to electricity after these conversion processes. Depending on the conversion process, they are coupled to the grid both indirectly or directly.

2.3.2.10 Conventional Fossil-Fuel Based Generators:

Within the category DG, the term “Conventional Fossil-Fuel Based Generators” is used to describe small fossil-fueled power plants within a range of kWs up to a few hundred of MWs, gas turbines and reciprocating engines are most common one in this type of generation [11].

Reciprocating engines are widely used as DG. They have a wide range of output from few kW to about 10 MW and are usually fuelled by diesel or natural gas. With development of modern emissions control technology, their impact to environment is low and also they can be run using biomass-derived fuels [4].

2.4 Energy Storage Systems

Distributed generation includes mostly generation type with non-controllable primary source. They have intermittent and unpredictable nature. Thus, these make integration of the DG to the grid a challenging task considering system security and reliability and continuity. Energy storage systems are the effective way of decreasing negative impacts of DG to the system.

Energy storage systems have been used in uninterruptable power supply (UPS) systems and off-grid applications for many years. However, it has newly started to be used for centralized applications to lessen the effect of DG in terms of maintaining customer supply standards (continuity of electricity, voltage and frequency). Furthermore, they can reduce the requirements for online generator reserves (spinning reserves) by supplying power for short durations during generation capacity deficiencies until offline generators can be started and brought online [16]. In the following parts, energy storage technologies are emphasized.

2.4.1 Battery Energy Storage Systems:

Battery Energy Store Systems (BSESS) are the most well-known electrical energy storage systems. Batteries store the energy in chemical form when charged and convert chemical energy into electrical energy during discharge. They can store rather large amounts of energy in small volumes and quickly response to load changes and their output power capacity is in the order of MWs.

Batteries are used as electrical energy storage in a wide variety of applications and different types of batteries are commercially available in the market for many years. Commonly used types of batteries can be listed as;

- Lead-Acid Batteries
- Nickel-Cadmium Batteries
- Sodium Sulfur Batteries
- Vanadium Redox Batteries
- Zinc-Bromine Batteries

2.4.2 Compressed Air Energy Storage Systems:

Compressed air energy storage (CAES) offers a method to store low-cost off-peak energy in the form of stored compressed air (in an underground reservoir or an aboveground piping or vessel system) and to generate on-peak electricity by releasing the compressed air from the storage reservoir, preheating the cool, high-pressure air or directing the preheated air into an expansion turbine driving an electric generator [17]. During discharges at peak loads, the compressed air is released to a combustor where the compressed air is mixed with oil or gas driving a gas turbine to create electrical energy [17].

Typical capacity for a CAES system are in the range of 50 -300 MW and their efficiency is around 85%. A typical compressed air energy storage system is shown in figure 2.7.

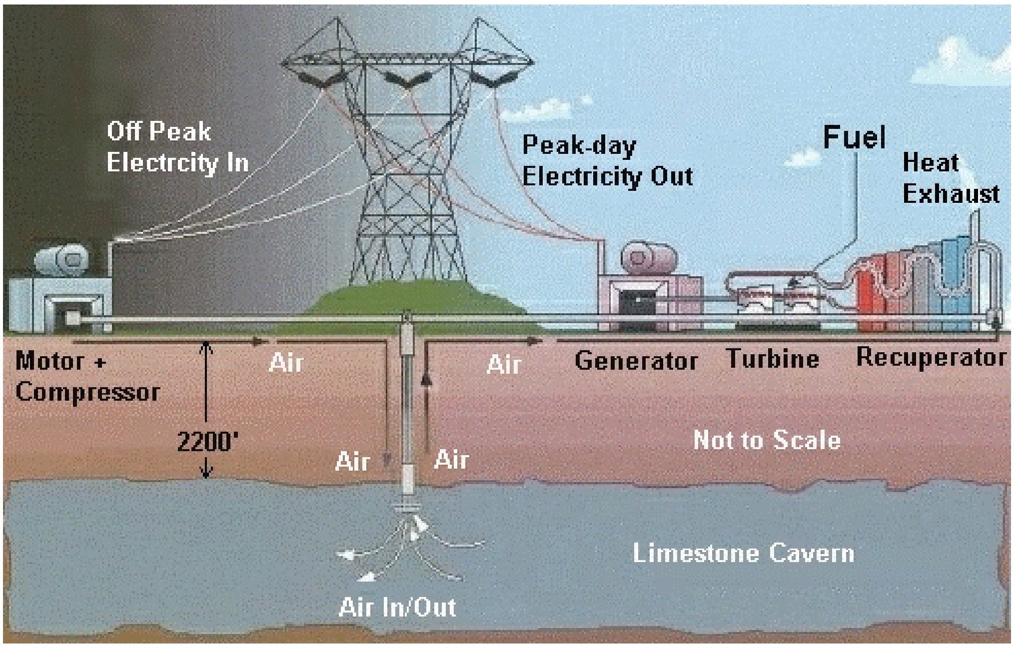

Figure 2.7: A typical compressed air energy storage system [17]

2.4.3 Pumped Hydro Storage Systems:

Pumped-hydro storage systems use off-peak power to pump water uphill to an elevated reservoir. When required, the water flow is reversed to generate electricity by the release of its potential energy. They are currently available and used for high power applications up to a few hundred MW with efficiency 60-80%. They are mainly used for energy management, controlling frequency and providing reserve.

2.4.4 Superconducting Magnetic Energy Storage Systems:

Superconducting Magnetic Energy Storage (SMES) systems convert off-peak AC power to direct current and fed into electromagnetic coil of superconducting cables to store energy. The coil is kept at superconductive temperature by a refrigeration system which is designed to meet the superconducting properties of the special materials used to fabricate the magnetic coil [18]. Stored energy can be released by discharging the coil.

Due to energy requirement of refrigeration system and high cost of super conducting cables, SMES systems are currently used for short duration energy storage. Yet, SMES systems are expected to have a promising future when taken into the consideration of their high efficiency (95% and over) and rapid charge and discharge capabilities.

2.4.5 Flywheel Energy Storage Systems:

Flywheel Energy Storage (FES) systems store energy in kinetic energy form and convert from kinetic to electric by electromechanical devices. Kinetic energy is stored as rotational energy and converted back by slowing down the flywheel.

Flywheels are the earliest discovered energy storage technologies (potter’s wheel). Nowadays, advanced flywheel developments include operating the wheel in a vacuum and replacing the standard bearing with a levitated magnetic bearing (using a conventional magnets, sometimes in concert with bulk superconductors) to reduce the bearing heat losses [18]. Cross-section of a flywheel module is depicted in figure 2.8.

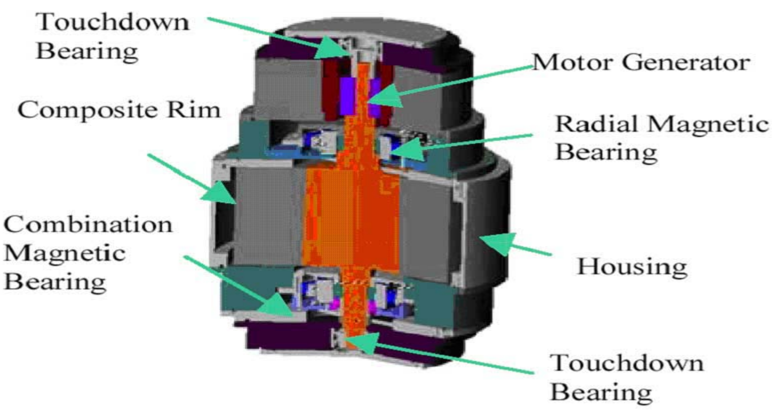

Figure 2.8: Cross-section of a flywheel module [17]

2.4.6 Ultracapacitors Storage Systems:

Ultracapacitors store energy in the form of electrostatic energy (static charge). Similar to a regular capacitor, the electric energy is stored by means of charge separation [11]. They are ideal for applications required high power and short-discharge (have less than about 1 second discharge time). But they are originally developed for military applications and they are still under the development for high-voltage utility applications.

2.4.7 Hydrogen Energy Storage Systems:

Hydrogen Energy Storage (HES) systems use hydrogen as a non-CO_2 producing fuel. They are mostly used for electricity production and electrical vehicles via fuel cells. Hydrogen fuel cells store energy in electrochemical form. Hydrogen is produced by electrolysis of water using the off-peak electricity such as coming from wind turbines, photovoltaics, hydro or even nuclear power plants and this hydrogen can be used to operate fuel cells when there is high demand for electricity [11].

CHAPTER 3

DYNAMIC ANALYSIS OF POWER SYSTEM

The function of electric power system is to convert proper energy forms in to electrical energy and transmit it to the consumption points. Power system consists of generating stations, transmission systems, distribution systems and loads. Transmission systems provide connection between generating stations and distribution systems and electricity is supplied to the loads through distribution systems.

Power system is a dynamic system and there should be balance between load and generation. Demand of load changes at any time; a well designed and operated power system should keep balance in case of demand increase or decrease and also encounter a disturbance.

The purpose of this chapter is to provide a general background about power system stability.

3.1 Power System Stability

Generally stability is ability of a system to remain unchanged in response to either to a disturbance or fluctuations of system due to a disturbance [19]. From the point of power system, stability is defined as the ability of an electric power system for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [20].

Power systems are subjected to a wide range of disturbances, small and large. Small disturbances are occurred in form of load changes. Load changes are inherent part of the power systems and occur continually. Besides maintaining stability after a small disturbance, also a stable power system must be able to survive in case of numerous disturbances of a severe nature, such as a short circuit on a transmission line or loss of a large generator.

Stability of a power system is related with the behavior of synchronous machines connected to the system. They supply power to the system in synchronism in steady state condition. If a disturbance does not create any change in power, machines should return to their original state. If a net change in power is occurred, machines should reach a new equilibrium state. In both case, all interconnected synchronous machines should not loss synchronism and remain operating in parallel at same speed.

3.2 Classification of Power System Stability

Power system stability is a single problem; however, the various forms of instabilities that a power system may undergo cannot be properly understood. Because of high dimensionality and complexity of stability problems, classification is essential for meaningful practical analysis and resolution of power system stability problems [20].

The classification of power system stability proposed here is based on the following considerations [21];

- The physical nature of the resulting mode of instability as indicated by the main system variable in which instability can be observed.

- The size of the disturbance considered which influences the method of calculation and prediction of stability.
- The devices, processes, and the time span that must be taken into consideration in order to assess stability.

Figure 3.1 gives the overall picture of the power system stability problem, identifying its categories and subcategories.

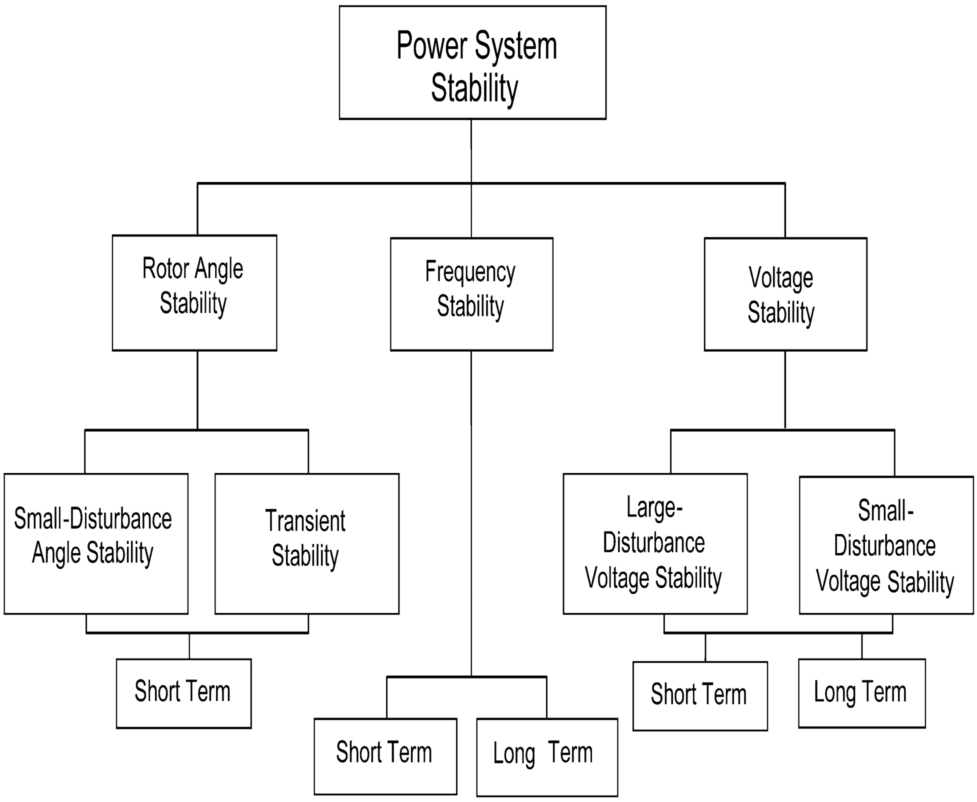

Figure 3.1: Classification of power system stability [20].

3.2.1 Rotor Angle Stability

Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to maintain equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators [20]-[21]

Power outputs of synchronous machines vary as their rotor angle change. In the equilibrium state, a synchronous machine connected to the power system operates at synchronous speed at constant rotor angle and mechanical power output is equal to the electric power input. If the system is perturbed, this equilibrium is upset, resulting in accelerating or decelerating of the rotors of the machines according to laws of motion of a rotating body [20]. If one of the generators runs faster than another as a result of a load change or a fault in the system, the angular position of its rotor relative to that of the slower machine will advance. This resulting angular difference transfers some part of the load from slow machine to fast machine. This power comes from the kinetic energy stored in the rotating system of fast machine. This resulted as speed increase in the rotor slow machine and speed decrease in the rotor of fast machine. This can be accomplished only by a increase in rotor angle of slow machine and decrease in rotor angle of fast machine. Hence, angular separation and speed difference decreases. Instability results if the system cannot absorb the kinetic energy corresponding to these rotor speed differences and loss of synchronism can occur between one machine and the rest of the system, or between groups of machines, with synchronism maintained within each group separating from each other [20].

Rotor angle stability can be categorized in two subcategories; small-disturbance (or small-signal) rotor angle stability and large-disturbance rotor angle stability or transient stability.

Small-disturbance or small-signal rotor angle stability is concerned with the ability of power system to maintain synchronism under small disturbances [20]. Small-disturbance stability depends on the initial operating state of the system. Small disturbances result in a small change in rotor angles of machines and small oscillations. If the oscillations are damped after sufficient time, system is stable. If on the other hand the oscillations continue indefinitely, the system is unstable.

Large-disturbance rotor angle stability or transient stability, as it is commonly referred to, is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. Transient stability depends on both the initial operating state of the system and the severity of the disturbance [20]. Designation dynamic stability is also used for transient stability in different literatures. This work mainly focuses on transient stability of power systems.

3.2.2 Voltage Stability

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition [20]. Instability occurs in the form of a progressive fall or rise of voltages of some buses. The term voltage collapse is also used.

A major factor contributing to voltage instability is the voltage drop that occurs when active and reactive power flow through inductive reactances of the transmission network; this limits the capability of the transmission network for power transfer and voltage support [20]. Voltage stability is classified into two subcategories as in the rotor angle stability;

Large-disturbance voltage stability refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies; small-disturbance voltage stability refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load [20].

The time frame of interest for voltage stability may extend from a few seconds to tens of minutes. Voltage stability may be either a short-term or a long-term phenomenon. The study of interest of short-term voltage stability is in order of several seconds and involves dynamics of fast acting load components. The study of interest of long-term voltage stability may extend to several minutes and involves slower acting equipments.

3.2.3 Frequency Stability

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain balance between generation and load. Instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads [20].

Severe system upsets generally result in large excursions of frequency, power flows, voltage, and other system variables, thereby invoking the actions of processes, controls, and protections that are not modeled in conventional transient stability or voltage stability studies. These processes may be very slow, such as boiler dynamics, or only triggered for extreme system conditions, such as volts/Hertz protection tripping generators. In large interconnected power systems, this type of situation is most commonly associated with conditions following splitting of systems into islands. Stability in this case is a question of whether or not each island will reach a state of operating equilibrium with minimal unintentional loss of load. It is determined by the overall response of the island as evidenced by its mean frequency, rather than relative motion of machines. Generally, frequency stability problems are associated with inadequacies in equipment responses, poor coordination of control and protection equipment, or insufficient generation reserve.

3.3 Indicators for Assessment of Stability of Power Systems

As discussed in the previous parts, a power system is subjected to the different disturbances during its operation and results change from situation to situation. A power system may be stable for one disturbance and unstable for another. Although it is possible to design a power system which can withstand all the different kinds and degree of disturbances and remains intact, it is never chosen due to its being an impractical and uneconomical design. When designing a power system, probability of occurrence of a disturbance is taken into the consideration and it is expected to maintaining stability after a high probability occurrence disturbance.

To assess the stability of a power system, it is needed to observe the behavior of power system after subjected to the disturbances. This can be achieved by power system indicators. Critical Clearing Angle (CCA) and Critical Clearing Time (CCT) are widely used as system stability indicators.

Critical clearing angle is that switching angle for which the system is at the edge of instability for a given fault and switching arrangement. Critical clearing time is the time when the power angle reaches the critical clearing angle during the first swing [22]. A power system is capable of maintaining its stability as long as the fault clearing time is less than CCT or the angle of the synchronous machine is less than the CCA. Power-angle relation, swing equations and equal-area criterion concept are described in Appendix C.

CCA and CCT are determined by time-domain numerical integration method for large power systems. Although it is practical to use CCA and CCT as indicators for two machine systems or one machine infinite bus system, the computer simulations are the only practical way to determine CCA and CCT for large power systems, and it requires repetitive time domain simulation runs.

In section 5.4, impacts of DG on stability are investigated by comparing the CCT of system at different penetration levels. However, in section 5.2 and 5.3 the focus is on the effects of different DG technologies on system for different penetration levels and fault durations. Much more simulations are needed to be run for these researches. Therefore, more practical stability indicators are needed to be used to assess the stability of power system. In these parts, maximum rotor speed deviation and oscillation duration are used as system stability indicators. It is assumed that if value of the both stability indicators are diminished, stability margin of the system is strengthened.

3.3.1 Maximum Rotor Speed Deviation

Maximum Rotor Speed Deviation is defined as the maximum rotor speed deviation value reached by a generator during or after fault [23]. It is depicted in Figure 3.2.

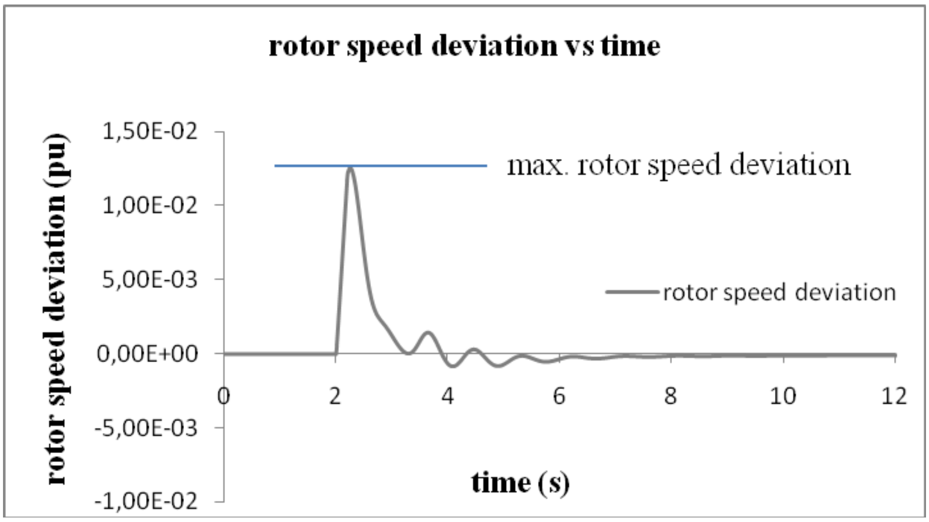

Figure 3.2: Transient stability indicator: Maximum rotor speed deviation

This is the indicator used to assess the performance of different cases from the point of rotor angle stability. It suggests that the more/faster the rotor speed (of the synchronous generators) deviates from the rated value when a disturbance occurs, the more instable the system becomes [11]. When two cases are compared with the same disturbance (same fault type and duration), a higher maximum rotor speed deviation means lower stability margin.

3.3.2 Oscillation Duration

The oscillation duration is defined as the time interval between the start of the fault, and the time at rotor angle (relative to reference synchronous machine) of the synchronous machines does not change more than 10^{-3} degree between simulation steps and 10^{-2} degree for a time period longer than 3 seconds. The oscillation duration of a generator can be obtained from the formulas below;

$$\text{Oscillation duration} = t_{osc} - t_f \qquad (3.1)$$

Where t_f is the time (s) when the fault is applied and

$$t_{osc} = \min\left\{t : \left(\left|\delta(t+n\Delta t) - \delta(t+(n-1)\Delta t)\right| \le 10^{-3}\right) \wedge \left(\left|\delta(t+3) - \delta(t)\right| \le 10^{-2}\right)\right\} \qquad (3.2);$$

where Λ is logic "and"; and $n = 1, 2, 3, ..., \frac{3}{\Delta t}$ (3.3);

where Δt is the simulation step (10^{-2} second is used in this study) and $\delta(t)$ is angle of generator

Oscillation duration is illustrated in figure 3.3.

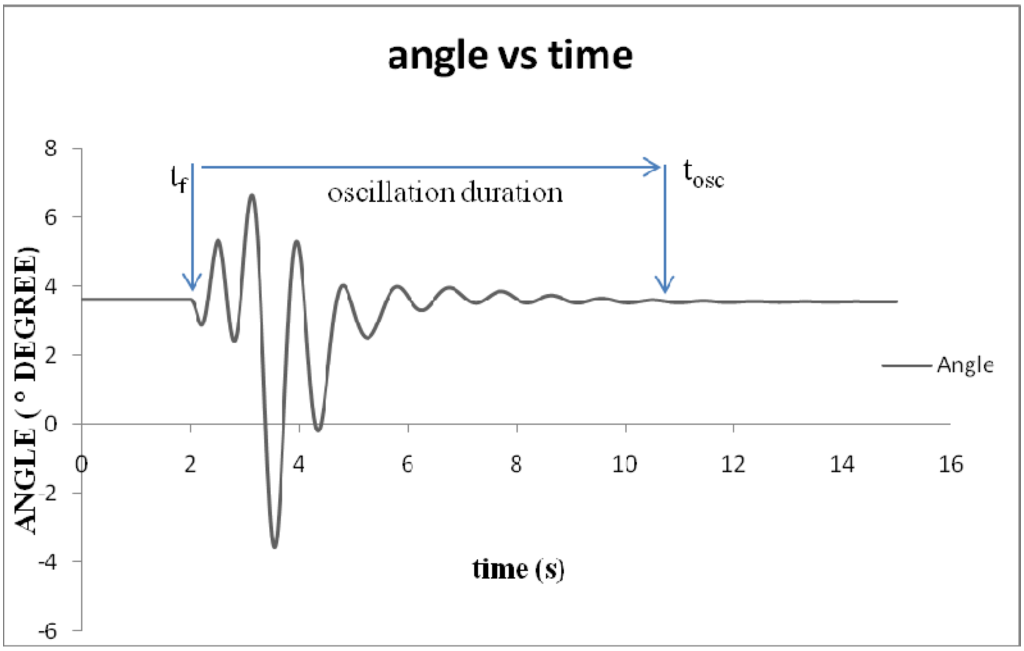

Figure 3.3: Transient stability indicator: Oscillation Duration

Oscillation duration is a measure for the time span that is needed to reach a new equilibrium after a disturbance [23]. It indicates that the shorter oscillation of rotor angle after a disturbance, the more stable system becomes.

CHAPTER 4

CASE STUDY- NEW ENGLAND (IEEE-39 BUS) TEST SYSTEM

This work is concerned in the effect of DG with different technologies on the transient stability of the transmission system while their penetration level is increasing. This is evaluated by comparing the strength of power system for different cases in terms of the transient stability.

Model of a power system is needed to assess the dynamic stability. For this purpose, New England (IEEE 39 bus) test system is used in this work. New England test system is a well-known, widely used test system for power system dynamic studies. As it has been an extensively used test system, the simulations obtained throughout this work can be compared with the other studies.

4.1 Power System Dynamic Analysis Software

Power system simulation software packages are the computer simulation programs focused on the operation of electrical power systems. Different power system analysis software packages are available in the market. These programs are mostly used by utilities for long term generation and transmission system expansion planning, short-term operational simulations and market analysis. In this study, Power System Simulator for Engineering (PSS/E) is used.

PSS/E is a package of programs for studies of power system transmission network and generation performance in both steady-state and dynamic conditions and it includes analysis of power flow and related network functions, optimal power flow, balanced and unbalanced faults, network equivalent construction and dynamic simulation. It is the most widely used commercial program among its types.

4.2 New England IEEE39-Bus Test System

New England test system is a simplified representation of the 345 kV transmission system in the New England region which consists of 10 Centralized Generators (CG) and 19 load buses. The characteristics and the single line diagram of New England test system are shown in Table 4.1 and Figure 4.1, respectively.

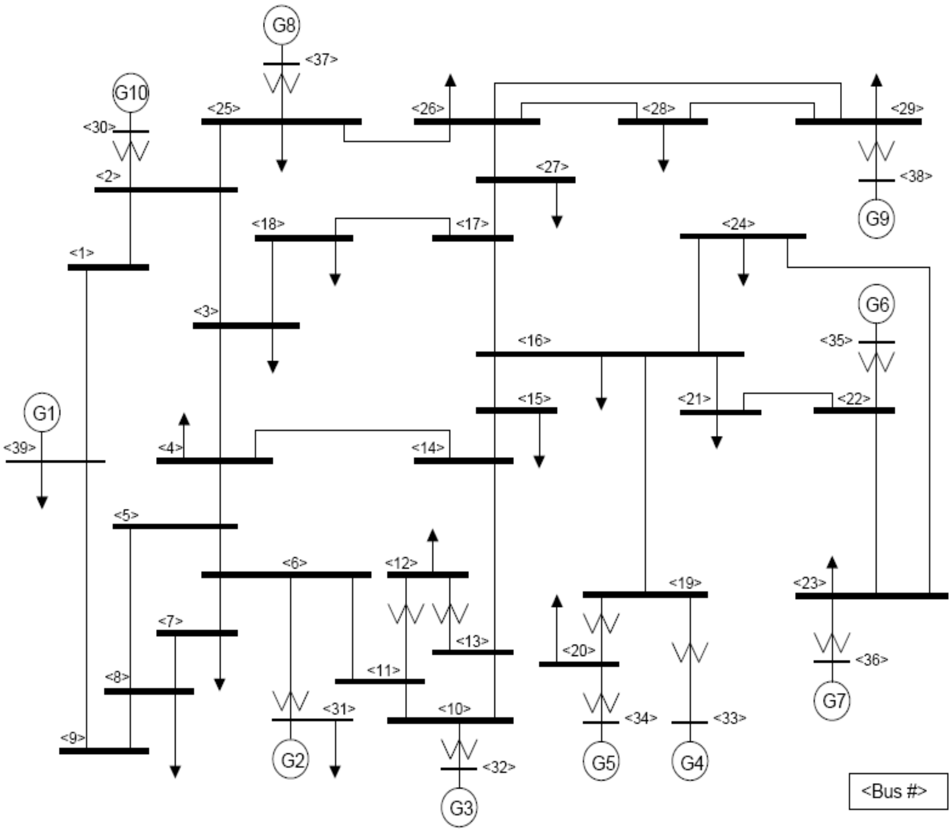

Figure 4.1: Single Diagram of New England (IEEE 39-bus) test system

Table 4.1 Characteristics of New England (IEEE 39-bus) test system

System Characteristics	**Value**
Number of buses	39
Number of generators	10
Number of transmission lines	46
Total generation	6144,9 MW/1340,5 MVAR
Total load	6098,5 MW/1408,9 MVAR

Parameters of the New England (IEEE 39-bus) test system have been obtained from the book titled “Energy Function Analysis for Power System Stability” [24]. In this study, the basic parameters of the test system are taken from [25] but some minor corrections are made according to [24] and the basic parameters of the system are listed in Appendix A.

Generator 1 (G1) is modeled as aggregation of large number of generators in the original test system and its inertia value is set to very high compared to the other generators in the system. To assess the dynamic stability and to be able to make comparison between different cases while different generator technologies are connecting to the system, no bus is modeled as an infinite bus and system parameters are adjusted accordingly.

Round rotor generator model is equipped with IEEE type DC1A excitation model and a steam turbine governor model is used for each CG. The details of these models are available in PSS/E standard library [26]. Values for the parameters of these models are taken from [21] and [11] and listed in Appendix B.

4.3 Transient Stability Simulation of New England IEEE39-Bus Test System

Transient stability of the test system is simulated by applying permanent three-phase fault to the mid-point of the line between buses 15 and 16, chosen arbitrarily. The line 15-16 carries 314 MW and 106 MVAR in the prefault condition. The fault is cleared by tripping the line 15-16 after three different fault durations: 100 ms, 150 ms and 200 ms. The system remains in synchronism for all different fault clearing times after disturbance. Rotor speed deviations of the CGs for fault clearing durations of 100 ms, 150 ms and 200 ms are given in Figure 4.2 and rotor angle deviations of the CGs reference to rotor angle of generation 2 (swing bus) for fault clearing durations of 100 ms, 150 ms and 200 ms are shown in Figure 4.3.

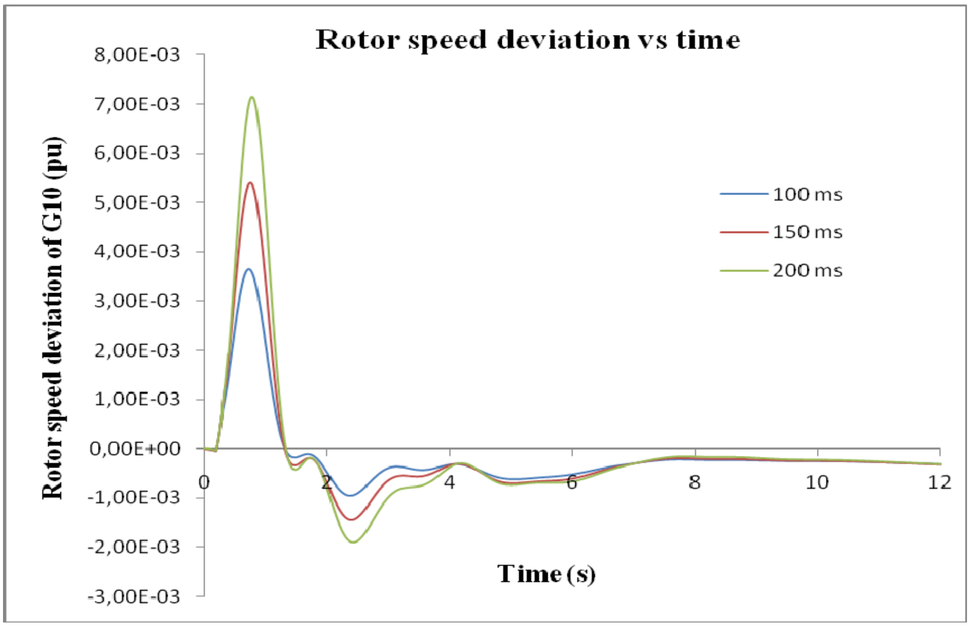

Figure 4.2: Base case: rotor speed deviation of G10 for different fault durations; 100 ms, 150ms, 200 ms.

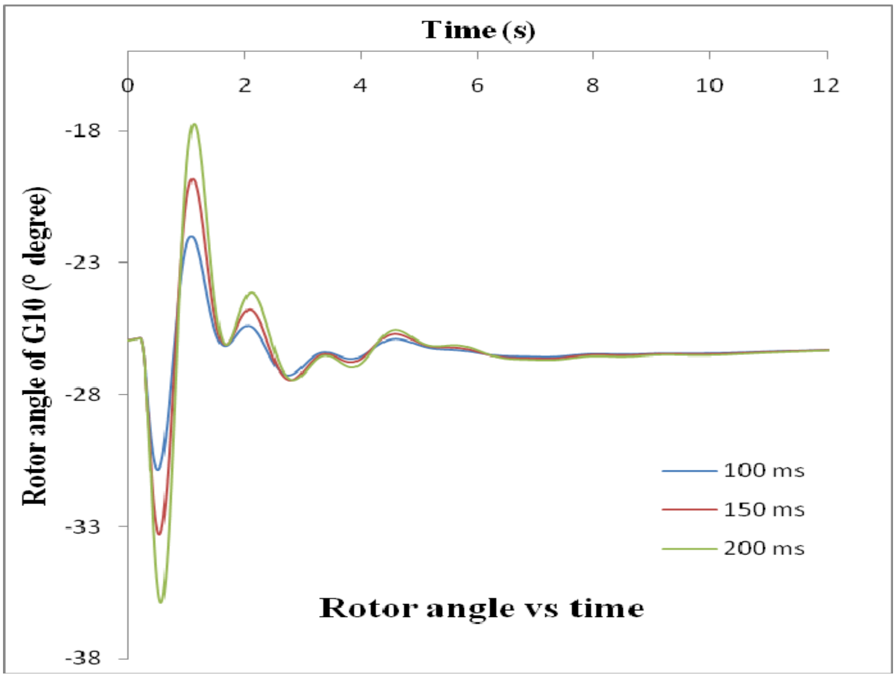

Figure 4.3: Base case: rotor angle deviation of G10 for different fault durations; 100 ms, 150ms, 200 ms.

4.3 Distributed Generation Technologies Connected To the New England IEEE 39-Bus Test System

Different available DG technologies are discussed in part 2.3. To investigate the impact of DG on the dynamic stability of power system, different DG technologies are connected to the test system and the changing of stability indicators for different cases are investigated.

DG technologies can be connected to the grid either directly or indirectly. Electrical rotating machines with power output is the same as or close to the system frequency are directly coupled to the system. DG with variable AC frequency power output and DG with DC power output are indirectly coupled to the grid via power electronic converters.

Standard dynamic models of DG technologies connected to grid via power electronic converter are not available in the library of power system simulation program (PSS/E) which is used in this study. Although their behaviors are similar to the constant PQ sources (negative load) and it is not practical to add them to the test system as negative loads. They should be implemented with their protection systems. They have different protection schemes. Depending on their protection system, they can be automatically disconnected from the system when the voltage of the DG bus drops below a certain value and reconnects as soon as the voltage recovers or can be kept connected to the system during a fault with power limitation (output current is needed to be limited with maximum rated current) .

General structure of DG technologies with power electronic converter interface is depicted in Figure 4.4.

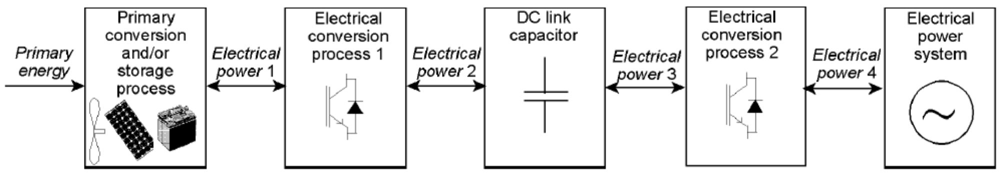

Figure 4.4 General structure of DG technologies with power electronic converter interface [27]

Implementing these technologies as a constant PQ source into the simulation programs is appropriate as long as the penetration of these technologies is low. Otherwise, detailed models of them are needed to be implemented. Investigating impacts of DG technologies connected to grid via power electronic converter are not covered in this study. In this study, four basic models are used for modeling different DG technologies to investigate the impact of DG on the transient stability of power system.

4.3.1 DG Connected to Grid as Negative Load

In the past, small generation units connected to the system are implemented to the power system simulation programs as negative loads (constant PQ sources). When the penetration level of these units is small, their effects on the transient simulation of overall system are negligible. However, when penetration level becomes increased, detailed models of these units are needed to be implemented to the simulation programs as discussed previously. To be able to make comparison, in terms of the impacts on dynamic stability, between when DG is implemented as negative load and when detailed models of distributed generators are used, the simulations are run while DG technologies connected to the grid as negative load.

4.3.2 Synchronous Generators

As discussed in part 2.3, synchronous generators are used in various DG technologies. Round rotor generator model which is available in PSS/E standard library [26] is used for the models of synchronous generators. Two different types of synchronous generators are used in this study as DG technologies. One is the synchronous generators with voltage and frequency control. In this model, each synchronous generator used as DG is equipped with IEEE type DC1A excitation model and a steam turbine governor model. The other is the synchronous generators without voltage and frequency control. The details of this models and representative values are attached in Appendix B.

4.3.3 Induction Generators

Induction generators are mostly used in small hydro-power plants and small wind turbines as DG. Induction generator with rotor flux transients (CIMTR3) model in PSS/E library is used for induction generator models and it is assumed that they are coupled to the grid directly. The details of this models and representative values are attached in Appendix B.

4.4 Connection of Distributed Generators to the Test System

In the test systems used for transient stability studies, the high-voltage transmission system is normally modeled in detail, while the distribution system is represented only by the load at the main connections between the transmission system and the distribution systems [11]. However, the structure of the distribution system is likely to change due to the increasing penetration level of DG. Generation, storage and load management are located within the distribution systems.

To assess the impact of DG on the stability of power system, a realistic and detailed model of distribution system including all load types, distributed generators and energy storage technologies is needed to be implemented. However, it is not practical to implement distribution system in details for the transmission system stability studies. A simple approach is to extend the current models to include the effects of the distribution system transformers and introduce an equivalent load and generator [28]. The form of the distribution system used in this study is given in Figure 4.5.

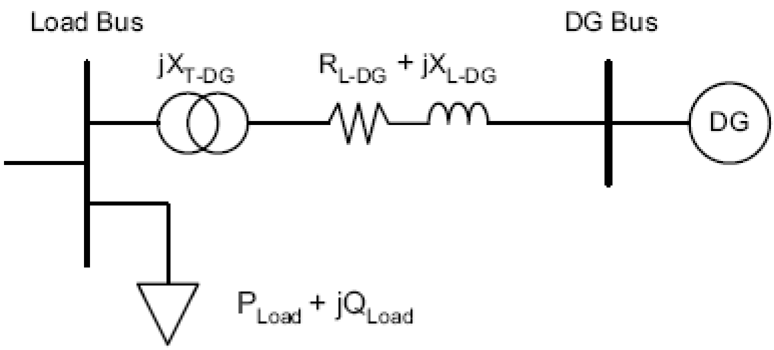

Figure 4.5: Model of connecting DG at a particular load bus [11]

In this model, X_{T-DG} and X_{L-DG} represent the reactances of transformer and the line between the DG bus and load bus, respectively. R_{L-DG} represents the resistance of the line. To simulate DG connected to the system from long distance, impedance parameters of the distribution model can be set a higher value. For the DG closer to the connection feeder, the system is simulated by decreasing these parameters. By

changing the values of these impedances, the impact of connection distance of DG on power system dynamics can also be observed.
In the parts 5.2, 5.3 and 5.4, X_{T-DG} and X_{L-DG} are set to a constant value and R_{L-DG} is neglected to make a comparison between different DG technologies. The same value is used for all simulation cases. Besides, to avoid causing confusion, only one DG technology is assumed to be implemented to the distribution system for one simulation case.

In the part 5.5, the impact of impedance value (X_{T-DG} and X_{L-DG}) on the stability is investigated by setting the impedance parameters to different value for different penetration levels. At low penetration levels, the impedance parameters of the connection of DG to the system are set to high values and at high penetration levels, impedance values are set to low.

CHAPTER 5

IMPACT OF DG ON THE TRANSMISSION SYSTEM TRANSIENT STABILITY (SIMULATION RESULTS AND DISCUSSIONS):

As mentioned in chapter 4, New England (IEEE 39 bus) test system is used to investigate the impact of DG on the transmission system transient stability while their penetration level is increasing. Different scenarios are developed and investigated on the test system. In this chapter, simulation scenarios are clarified, results are illustrated and discussions are made on the results.

5.1 Simulation Scenarios

To assess the impact of different DG technologies with different penetration levels, a simulation methodology requires to be developed to be able to make comparison between results of the simulations and observe how DG affect the system stability.

Firstly, a definition of DG penetration level should be stated. In this study, the penetration level of DG is assumed as the proportion of the power generated by the distributed generators to the total power generation in the system; it can be formulized as [28];

$$\%DG_{penetration\ \ level} = \frac{P_{DG}}{P_{DG} + P_{CG}} x100 \tag{5.1}$$

Where, P_{DG} is the total active power generated by DG technologies and P_{CG} is the total active power generated by the centralized generators.

The details of the simulations are as follows;

- DG technologies are connected to the each load bus as discussed in part 4.4. Total value of X_{T-DG} and X_{L-DG} are set to j0.05 pu on the 100 MVA system base and R_{L-DG} is neglected (Fig. 4-8) in the parts between 5.2 and 5.4. This impedance value is kept constant for all simulation cases in these parts.

- As discussed in part 4.3, to investigate the effect of DG on the transmission system transient stability, the test system is simulated with the connection of four different DG technologies to the grid; synchronous generator with grid voltage and frequency control, synchronous generator without grid voltage and frequency control, induction generator and constant PQ-source in the parts 5.2 and 5.3. In these parts, in each simulation case, only one DG technology is implemented to the system. However, in the parts 5.4 and 5.5 the effect of DG on the transmission system is assessed by connecting DG technologies expect constant PQ-source to the arbitrarily chosen six load buses of the test system in the same simulation cases.

- The penetration level of DG can be changed by two possible ways. In the one scenario, the total generation of CG is kept constant, and real and reactive power consumption of the all loads is increased. The increased power demand of the system is met by the implemented DG. In the other scenario, power consumption of all loads is kept constant, and the power generation of CG is reduced. This missing power demand is supplied by the distributed generators connected to the load buses. In the parts 5.2 and 5.3, the second one is applied with the details below;

- Power output of CG is decreased in steps of 5% down to 40%, except for the swing bus (Generator 2, see Fig.4.1). Its power is changed during the solution of the load flow for covering network losses. However, as the generation of DG is increasing, its output power is reduced approximately proportional to the level of the penetration of DG.

- Firstly, the distributed generators are connected to the every load buses with a power output equal to 5% of load of the bus where it is implemented. Then, their power output is increased in steps of 5% of the load up to 40%. Therefore, the penetration level of DG is increased in steps of 5% up to 40% (Due to the loss of the system, the power output of G2 (swing bus) changes and it is not possible to reduce the power output of G2 in steps of exactly 5%. As an example at penetration level 10%, the total power generation from DG is 609.85 MW, the total power generation from CG is 5530.72 MW and the penetration level is 9.93% (from equation 5.1).Therefore, the effect of the loss of the system on the penetration level is neglected.). Consequently, eight penetration level scenarios are created for each implemented DG technologies. The increase of DG penetration level above 40% is not considered as realistic

- It is assumed that DG is operated at unity power factor and the reactive power consumption of the system is covered by CG.

- In the base case, no DG is implemented to the test system.

▪ In each simulation case, three phase permanent fault is applied to mid-point of the line 15-16. The fault is cleared by tripping the line 15-16 after three different fault durations: 100 ms, 150 ms and 200 ms. Eventually, three sub-scenarios are created for each penetration level scenario and for each implemented DG technology.

- It is assumed that none of the CG and the distributed generators is disconnected during and after the applied fault.
-

5.2 Simulation Results

The impacts of different DG technologies, DG penetration levels and fault durations on the transmission system transient stability are investigated through the simulations of the test system according to the scenarios described in part 5.1. To assess the system stability, maximum rotor speed deviation and maximum rotor angle oscillation duration are used as the stability indicators as described in part 3.3.1 and 3.3.2, respectively. To investigate the results in detail, the results are given and commented individually for each DG technologies implemented to the test system; synchronous generator with grid voltage and frequency control, synchronous generator without grid voltage and frequency control, induction generator and constant PQ source.

5.2.1 Synchronous Generator with Grid Voltage and Frequency Control

The results of the simulation show that if the synchronous generators with grid voltage and frequency control are implemented to the system as DG, the system is strengthened in terms of the transient stability for all fault durations and further the weakest centralized generators, having the lower indicator values, are affected more positively while DG penetration level is increasing.

The worst and the average value of max. rotor speed deviation of centralized generators are shown in Figure 5.1 and Figure 5.2, respectively.

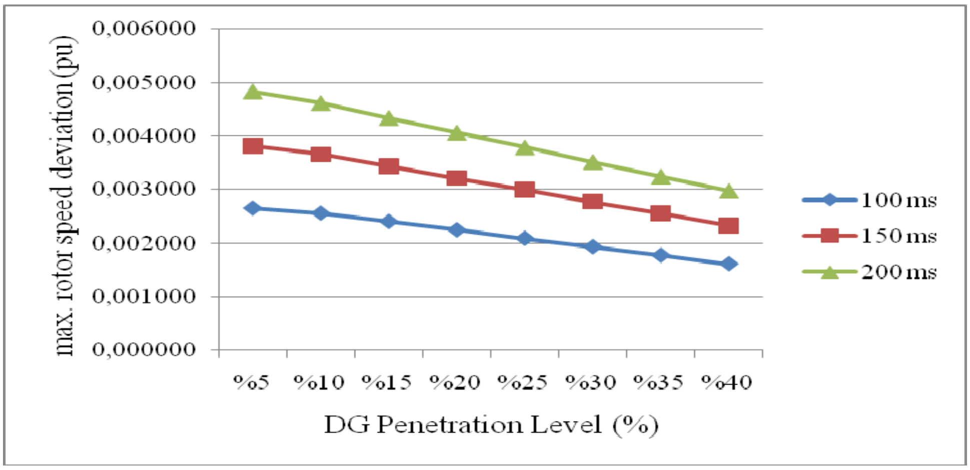

Figure 5.1: Worst value of max. rotor speed deviation of centralized generators when synchronous generators with grid voltage and frequency control are used as DG for fault clearing durations 100 ms, 150 ms and 200 ms.

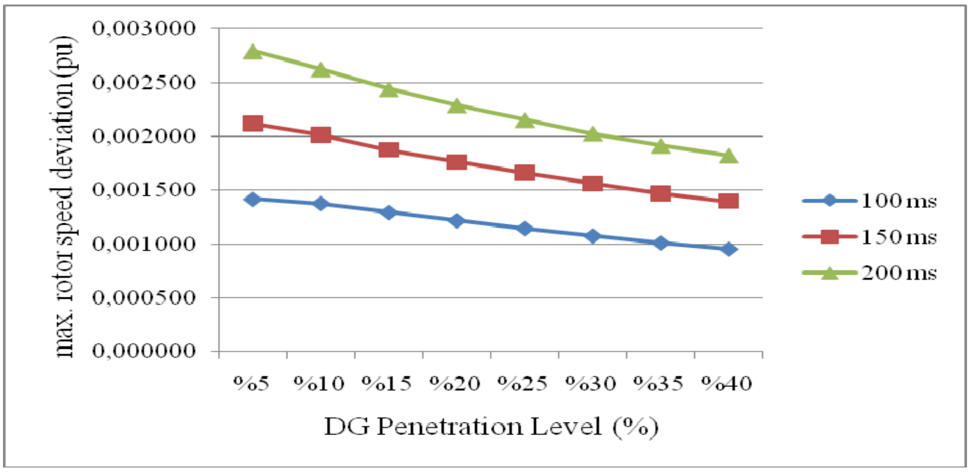

Figure 5.2: Average value of max. rotor speed deviation of centralized generators when synchronous generators with grid voltage and frequency control are used as DG for fault clearing durations 100 ms, 150 ms and 200 ms.

The graph showing the worst value of max. rotor speed deviation of CG is obtained by selecting the worst value of max. rotor speed deviation among all CG at each penetration level and the one which shows the average value of max. rotor speed deviation of CG is obtained by taking the average value of max. rotor speed deviation of all CG at each penetration level. Both graphs show that the stability margin of the system increases continuously for all fault durations while penetration of DG is increasing.

The indicator shows a similar tendency but with the different slopes in the both graphs. The worst value of max. rotor speed deviation of the centralized generators has fallen with a higher slope than the average max. rotor speed deviation of the centralized generators for all three fault durations. This shows that each centralized generator responded differently with the implementation of DG to the system. Figures 5.3, 5.4 and 5.5 show max. rotor speed deviation of each centralized generator for fault durations, 100 ms, 150 ms and 200 ms, respectively.

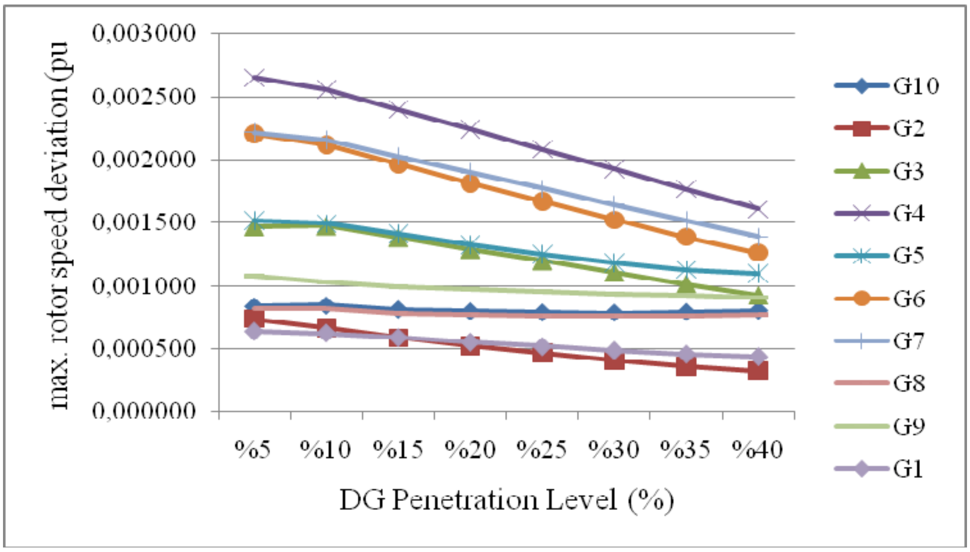

Figure 5.3: Max. rotor speed deviation of each centralized generator when synchronous generators with grid voltage and frequency control are used as DG for fault clearing durations 100 ms

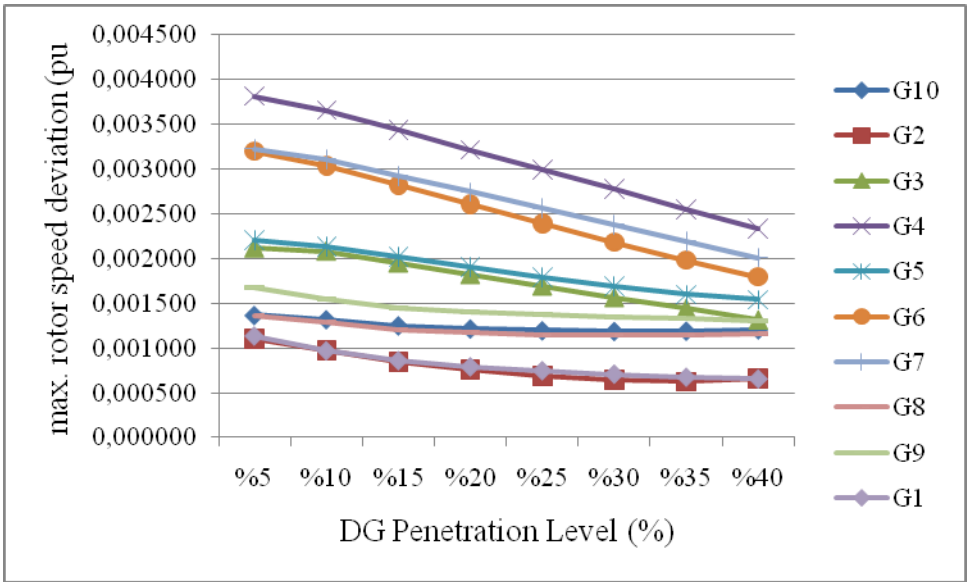

Figure 5.4: Max. rotor speed deviation of each centralized generator when synchronous generators with grid voltage and frequency control are used as DG for fault clearing durations 150 ms

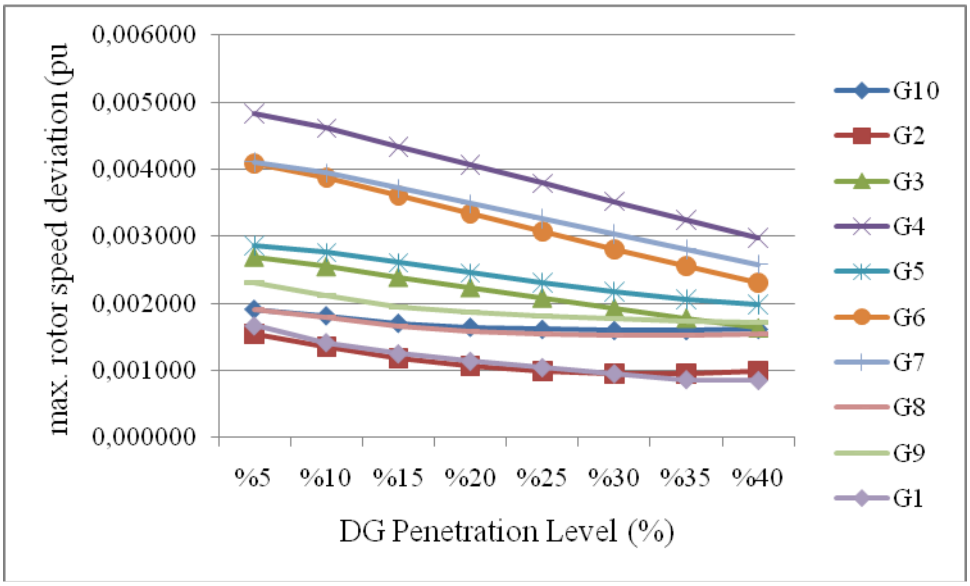

Figure 5.5: Max. rotor speed deviation of each centralized generator when synchronous generators with grid voltage and frequency control are used as DG for fault clearing durations 200 ms

Although Generator 4 (G4) does not have the worst max. rotor speed deviation in the base case, it shows the worst value of max. rotor speed deviation with the penetration of DG for all fault clearing times. As the reason for this, it can be said that Generator 4 is located far away from the buses to which the distributed generators are implemented and it is affected less from the implementation of DG than other CG. Even the rotor speed deviation of G4 shows improvement while the penetration of DG is increasing; it is the weakest CG at each penetration level concerning the rotor speed deviation.

Max. rotor speed deviations of Generator 1 (G1) and Generator 2 (G2) show certain improvement while the penetration level of DG is increasing up to 25%, but they remain constant for further implementations of DG. Additionally, max. rotor speed deviation of Generator 10 (G10) and Generator 8 (G8) are almost constant for all the penetration levels. It can be explained as follows; these four generators are located at the same side of the system and they behave like a group. Their responses to a disturbance in the system are expected to be more similar between each others compared to the generators located away. This area includes the strongest generator in the system (G1) and the biggest load at the same generator bus 39 (1104 MW). Thereby, in the base case, the load flow of this group is similar to the cases with DG (the load at bus 39 is supplied by the closest generator which is the G1 connected to the same bus). Hence, as the operation of the system is similar in the all cases, it is not expected to observe a significant impact of DG penetration on the generators belonging to this group.

The implementation of the synchronous generators with control also improves the CG in terms of the oscillation duration however it shows an inexplicit tendency for different penetration levels and fault durations. The oscillation durations are displayed in Figure 5.6 for different cases when considering the controlled synchronous generators are coupled to the system.

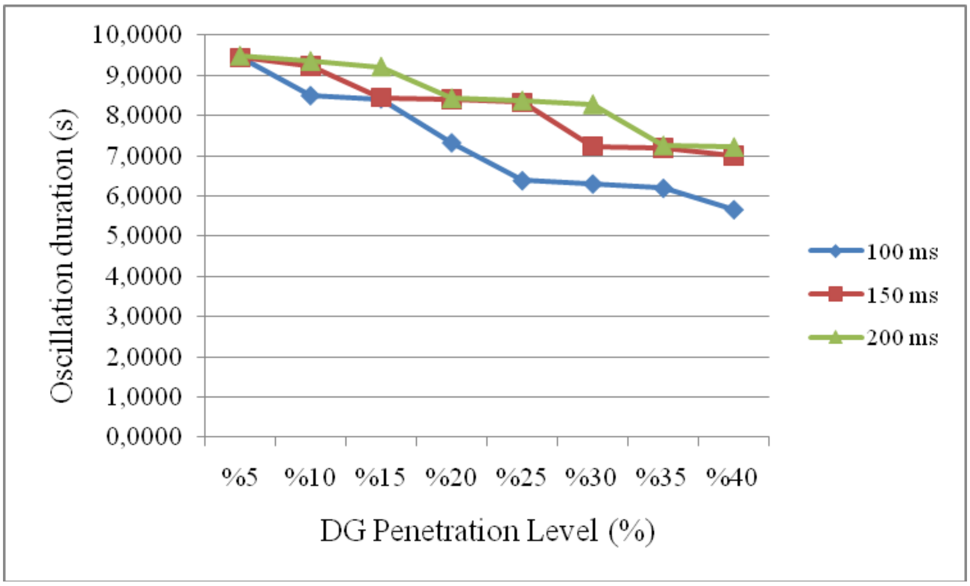

Figure 5.6: Worst value of oscillation duration of centralized generators when synchronous generators with grid voltage and frequency control are used as DG for fault clearing durations 100 ms, 150 ms and 200 ms.

The oscillation durations are almost the same for all three fault clearing times at the penetration level 5%, then they start to show different tendency for fault clearing times 150 ms and 200 ms. The oscillation duration for 100 ms fault duration is generally decreased with the increasing penetration level. For the fault clearing times 150 ms and 200 ms, it is fluctuated parallel except at the penetration levels 15% and 30%. Although the decrement of the oscillation duration is not obvious as for the fault duration 100 ms, the oscillation durations show also improvement for 150 ms and 200 ms fault clearing times. This can be explained as follows; when the lines are heavily loaded, the connection between the generators and the loads are weakened and the oscillation durations of the CG are increased. Implementation of DG decreases the load of the line by local generation and consumption. This is resulted in less oscillation of CG. That is expected for all the implemented DG technologies but as discussed in the following parts; it shows difference depending on the implemented technologies.

5.2.2 Synchronous Generator without Grid Voltage and Frequency Control

When the synchronous generator without grid voltage and frequency control is used as DG, the result of the worst value of max. rotor speed deviation of the centralized generators is almost same as the result when the synchronous generators with grid voltage and frequency control are implemented. The results can be explained as follows. Both uncontrolled and controlled distributed synchronous generators are equipped with an excitation winding on the rotor, keeping the generators excited during the fault. When a fault occurs, the distributed generators supply the fault current and the voltage dropping during the fault is not as severe as in the case without DG. Thus during the fault, a higher DG penetration level results in a higher terminal voltage and less over speed [11]. However the results are not the same when the average value of max. rotor speed deviation of centralized generators is considered.

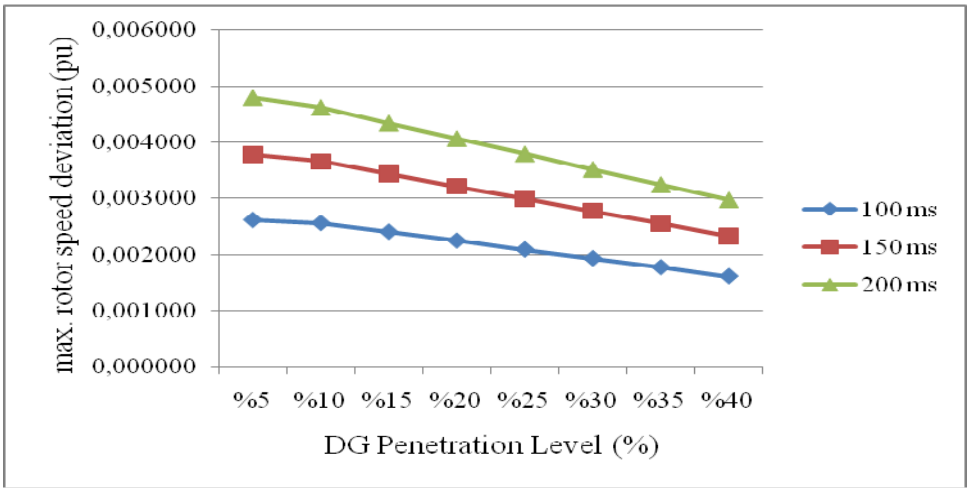

Figure 5.7: Worst value of max. rotor speed deviation of centralized generators when synchronous generators without grid voltage and frequency control are used as DG for fault clearing durations 100 ms, 150 ms and 200 ms.

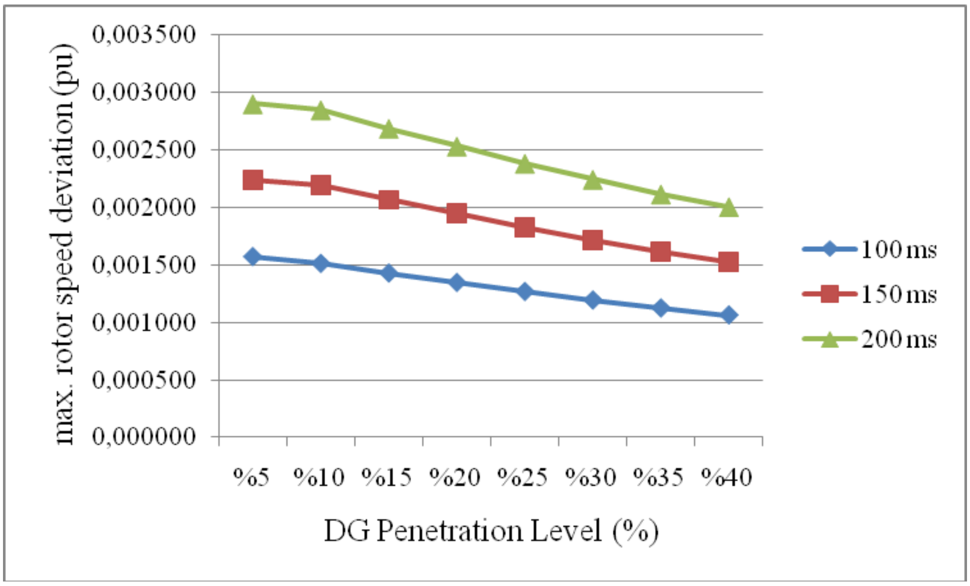

Figure 5.8: Average value of max. rotor speed deviation of centralized generators when synchronous generators without grid voltage and frequency control are used as DG for fault clearing durations 100 ms, 150 ms and 200 ms.

At the first glance, the difference between the implementations of controlled and uncontrolled DG is distinguished on the average value of max. rotor speed deviation of the centralized generators. In the controlled one, the indicator shows an improvement immediately after the implementation of DG to the system. However, in the uncontrolled one, the average value of max. rotor speed deviation of the centralized generators remain almost constant up to 10% DG penetration level and then starts to show a noticeable improvement. To investigate the behaviors of the centralized generators separately while the penetration levels of the uncontrolled synchronous generators are increasing, the graphs of max. rotor speed deviation of each centralized generator for fault durations, 100 ms, 150 ms and 200 ms are shown separately in Figures 5.9, 5.10 and 5.11.

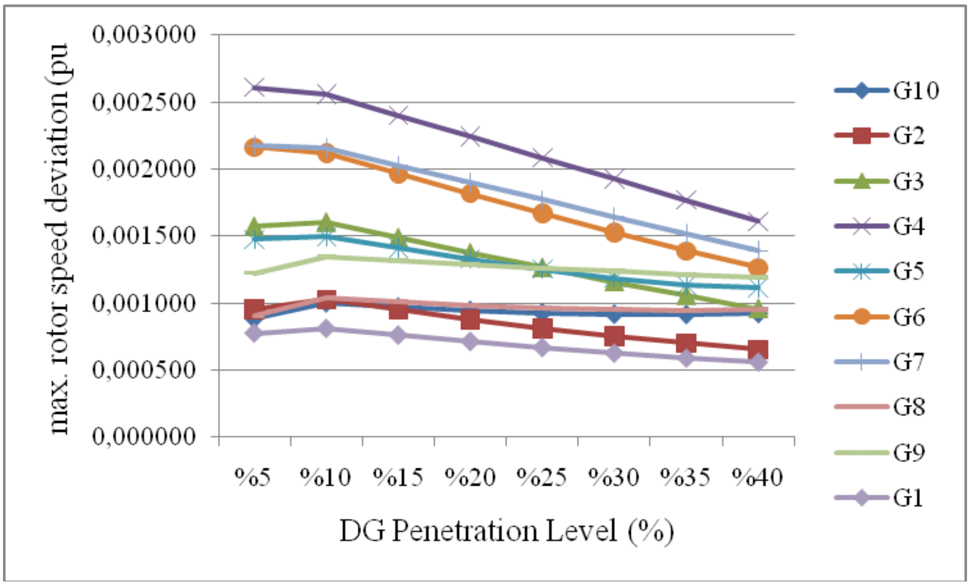

Figure 5.9: Max. rotor speed deviation of each centralized generator when synchronous generators without grid voltage and frequency control are used as DG for fault clearing durations 100 ms

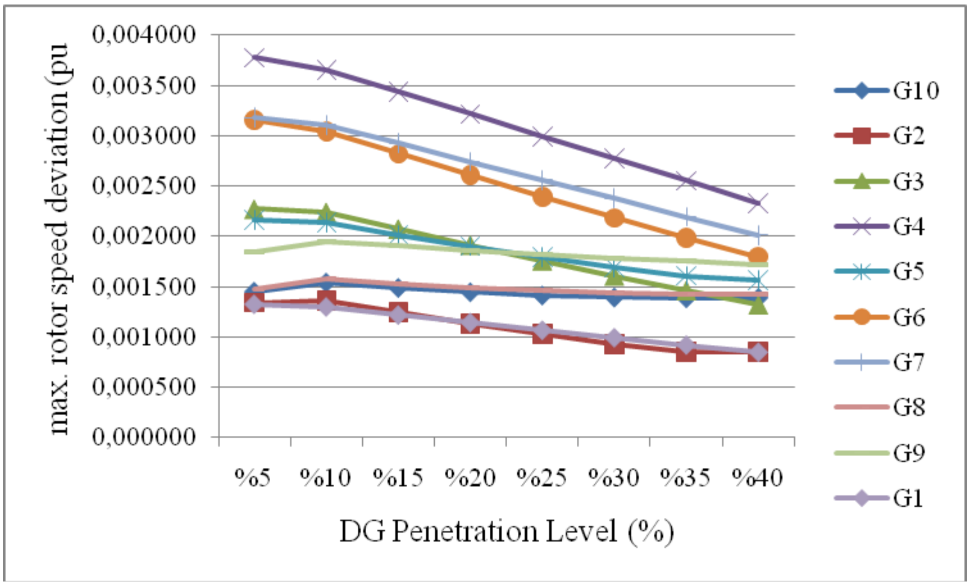

Figure 5.10: Max. rotor speed deviation of each centralized generator when synchronous generators without grid voltage and frequency control are used as DG for fault clearing durations 150 ms

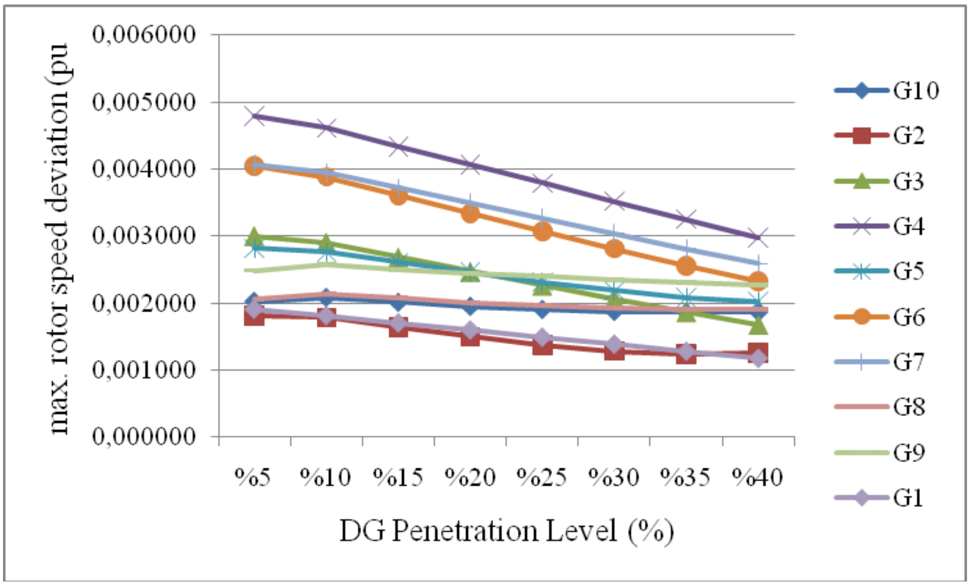

Figure 5.11: Max. rotor speed deviation of each centralized generator when synchronous generators without grid voltage and frequency control are used as DG for fault clearing durations 200 ms

Again, max. rotor speed deviations of G8 and G10 remain constant and G4 has the worst max. rotor speed deviation while the penetration of DG is increasing. In this scenario, however, max. rotor speed deviations of G1 and G2 remain unchanged up to 10% penetration level and then start to show certain improvement up to 40% penetration level.

When the oscillation duration is considered, the uncontrolled case is differed by the controlled one. As mentioned in part 5.2.2, a certain improvement is observed on the oscillation duration of CG when the controlled synchronous generators are coupled as DG. However, the same result cannot be deduced for the uncontrolled case. The oscillation duration of CG decreases at low-level penetration but it remains constant for further penetration levels. The effects of the penetration of DG on the oscillation duration of CG may not be seen due to the increasing install capacity of the generators without control systems while the installed capacity of the generators with control systems is decreasing.

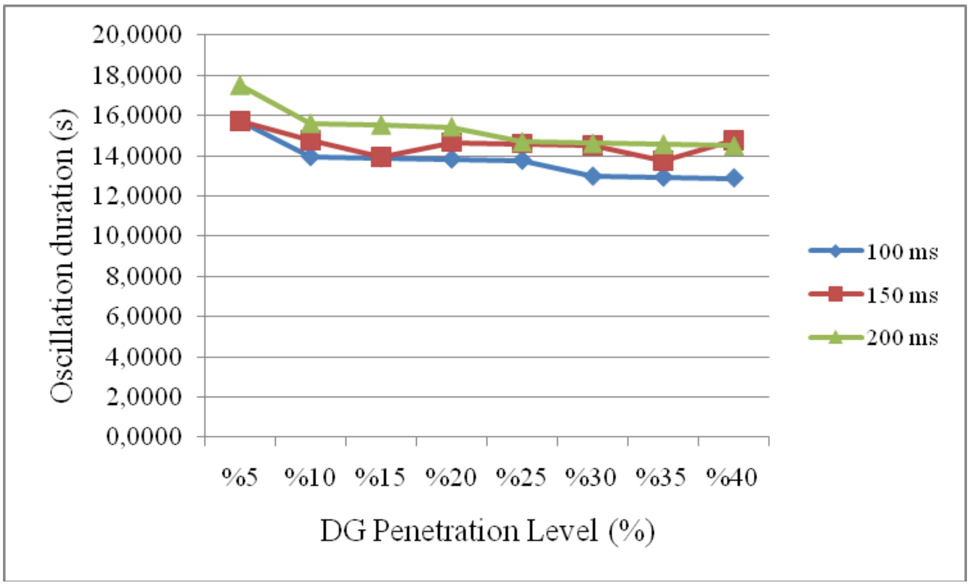

Figure 5.12: Worst value of oscillation duration of centralized generators when synchronous generators without grid voltage and frequency control are used as DG for fault clearing durations 100 ms, 150 ms and 200 ms.

5.2.3 Induction Generators

Figure 5.13 and Figure 5.14 show the worst and the average values of max. rotor speed deviation of the centralized generators when DG with induction generator technology used for the fault durations, 100 ms, 150 ms and 200 ms, respectively.

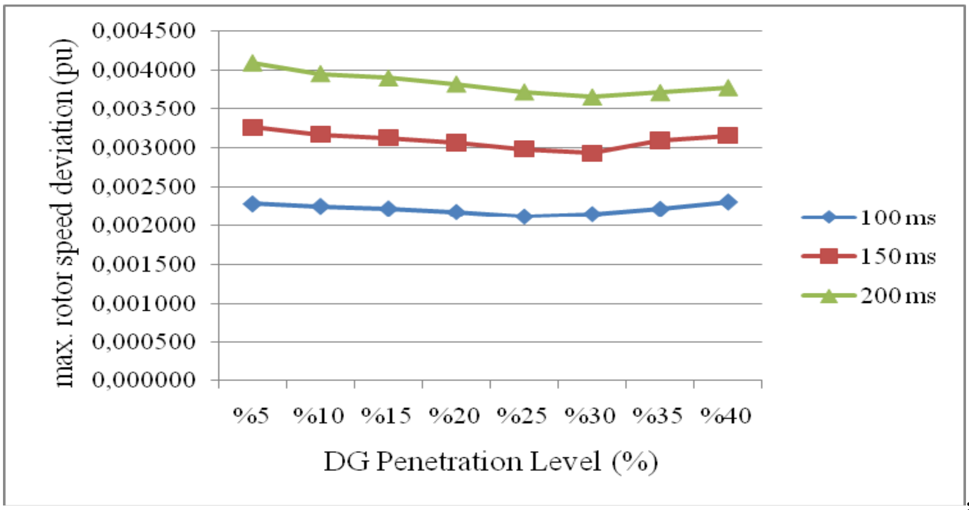

Figure 5.13: Worst value of max. rotor speed deviation of centralized generators when induction generators are used as DG for fault clearing durations 100 ms, 150 ms and 200 ms.

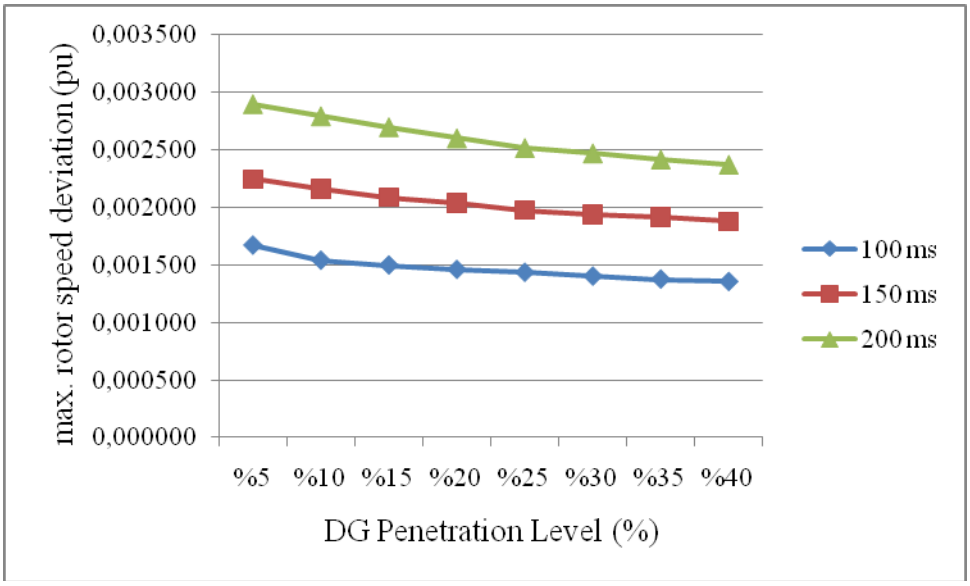

Figure 5.14: Average value of max. rotor speed deviation of centralized generators when induction generators are used as DG for fault clearing durations 100 ms, 150 ms and 200 ms.

For 100 ms and 150 ms fault durations, the worst value of max. rotor speed deviation tends to decrease up to the penetration level 30%, then increase for further penetration levels. For 200 ms, it shows a similar tendency; it tends to increase up to 25% penetration level and then starts to grow. It can occur due to the followings. The induction generators are widely used for small applications when directly coupled to the system due to the frequency deviation (part 2.3.6). Implementing induction generators at high penetration levels may negatively affect the rotor speed as well as the oscillation duration and reduce the stability margin of the system.

On the other hand, the average values of max. rotor speed deviation of the centralized generators consistently decrease for all fault durations. It could be arisen from that the some of the generators are affected positively by the implementation of the induction generators as DG and the some of them are affected negatively. In addition, the tendency of the indicator changes with the increasing penetration level. When figured the max. rotor speed deviation of each generator separately, a better judgment can be made.

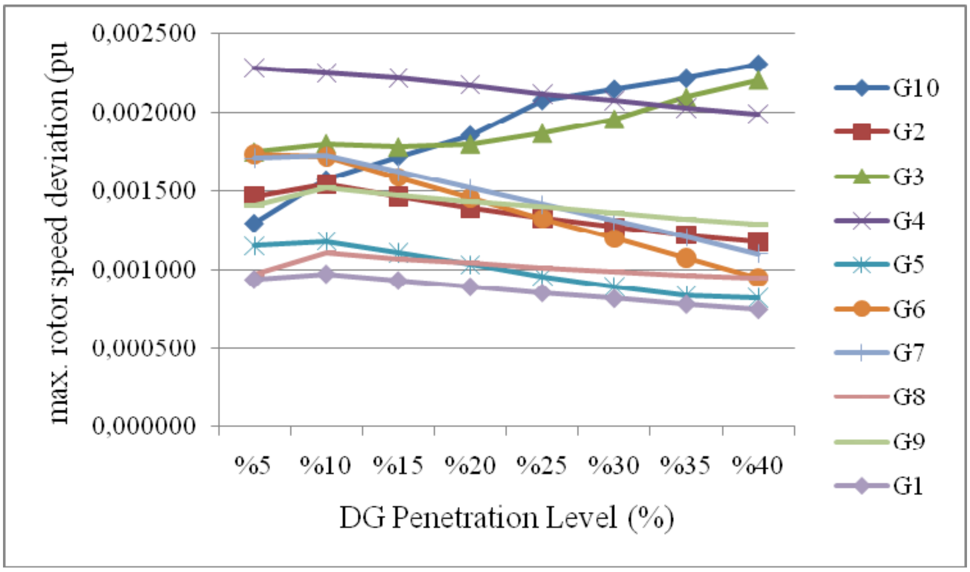

Figure 5.15: Max. rotor speed deviation of each centralized generator when induction generators are used as DG for fault clearing durations 100 ms

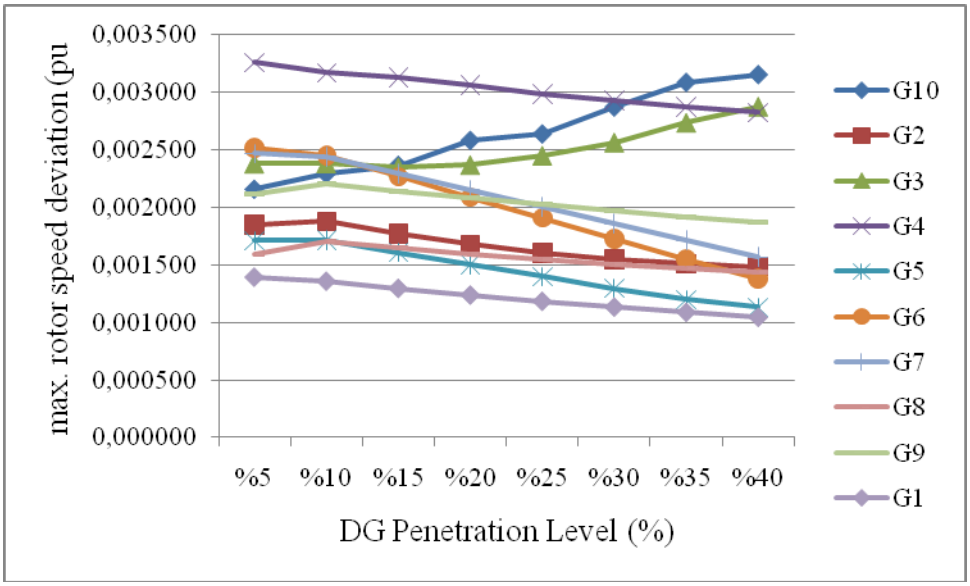

Figure 5.16: Max. rotor speed deviation of each centralized generator when induction generators are used as DG for fault clearing durations 150 ms

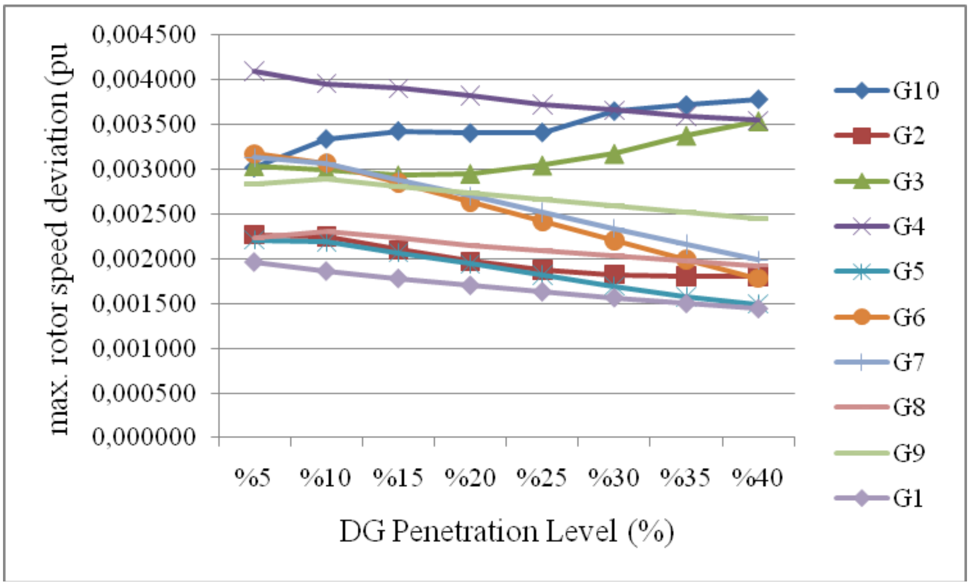

Figure 5.17: Max. rotor speed deviation of each centralized generator when induction generators are used as DG for fault clearing durations 200 ms

Max. rotor speed deviation of Generator 3 (G3) grows consistently with the increasing penetration level for all fault durations. Max. rotor speed deviation of G10 shows a similar tendency except for 200 ms fault duration in which it remains constant for the penetration levels between 15% and 25%. Max. rotor speed deviations of the other generators tend to decrease with the increasing penetration level. The reason of that could be explained as follows; the effect of the induction generators on stability depends on their distance to the centralized synchronous generators. The speed of the asynchronous generators is increased during the fault and these results in the increase of the stator frequency. If they are located near to the synchronous generators, they lead to the slowdown of the speed of the synchronous generators by decreasing the slip frequency and generated power. However, when they are placed with a large distance, they lead to a faster increase in rotor speed by increasing the reactive power demand and by lowering the terminal voltage due to speeding up during fault.

Implementation of IG as DG has less effect on the transient stability of the power system compare to the other technologies. At the certain penetration levels, they lead to an improvement and at some levels, to a decline of the system stability. Still, stability margin of the system does not change so much. This can be probably due to the opposite effects of near and remote implemented induction generators. This is also observed on the oscillation duration

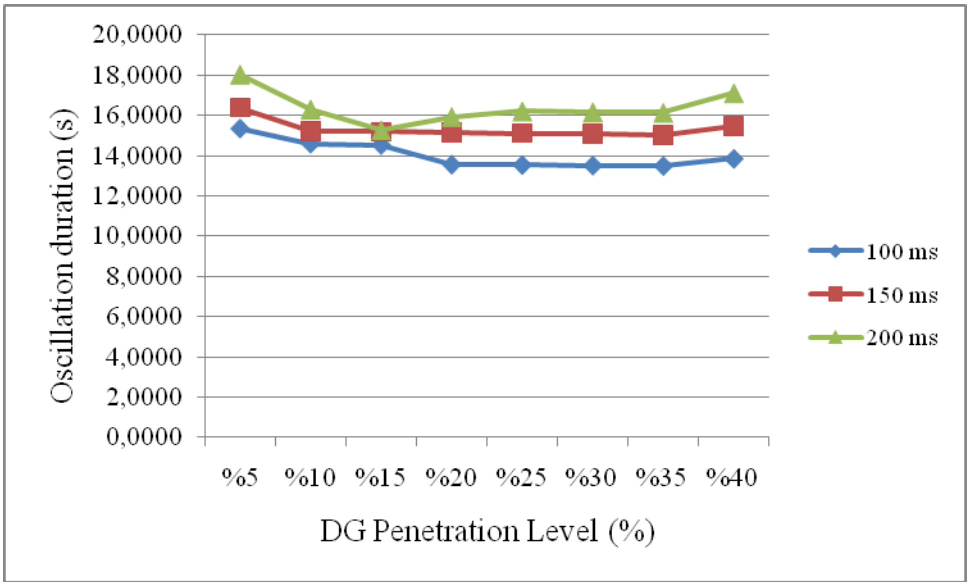

Figure 5.18: Worst value of oscillation duration of centralized generators when induction generators are used as DG, for fault clearing durations 100 ms, 150 ms and 200 ms.

5.2.4 Constant PQ Source (Negative Load)

In the earlier stability studies, DG is implemented to the systems as constant PQ-source regardless of what kind of technology is used. When they are implemented as constant PQ-source, power flow of the system is reduced and the lines are less loaded. As the models of connected technology are not implemented to the system, technology effect on the stability is also not taken into account. Since the implementing DG is a natural way of limiting the power flows over the transmission lines, it is expected to be seen a consistently decrease on the max. rotor speed deviation and oscillation duration of CG with the increasing penetration level.

The following figures show the behaviors of the indicators for different penetration levels and the fault durations.

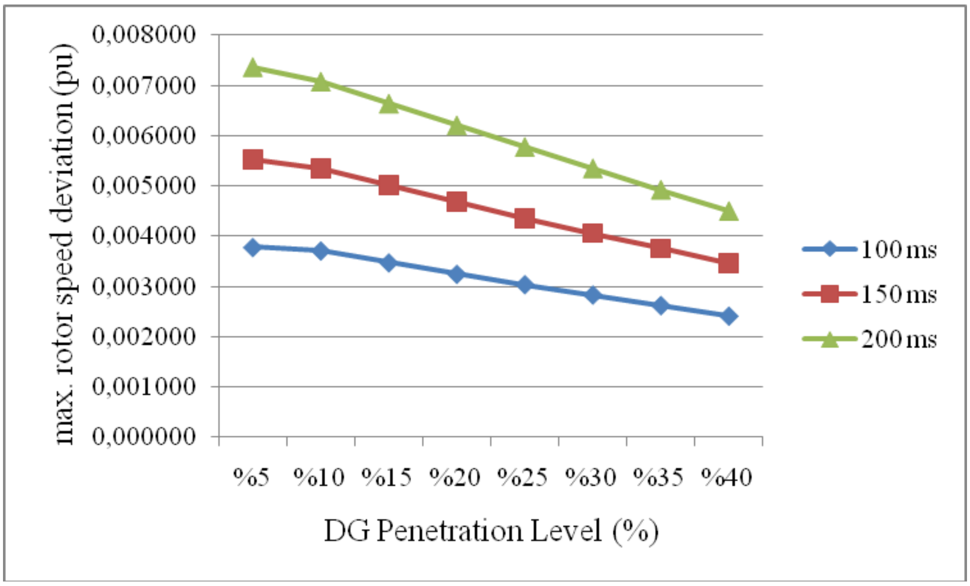

Figure 5.19: Worst value of max. rotor speed deviation of centralized generators when DG is connected as constant PQ source for fault clearing durations 100 ms, 150 ms and 200 ms.

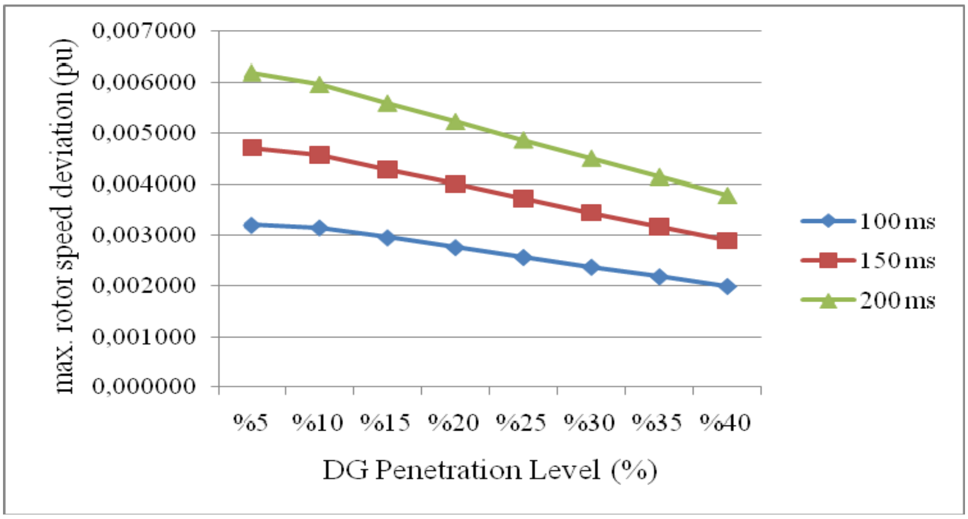

Figure 5.20: Average value of max. rotor speed deviation of centralized generators when DG is connected as constant PQ source for fault clearing durations 100 ms, 150 ms and 200 ms

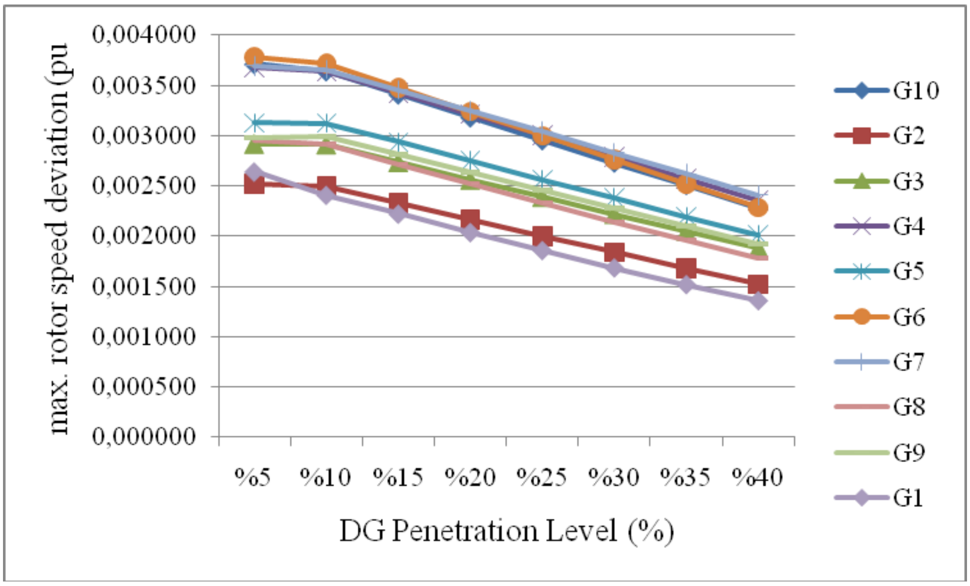

Figure 5.21: Max. rotor speed deviation of each centralized generator when DG is connected as constant PQ source for fault clearing durations 100 ms

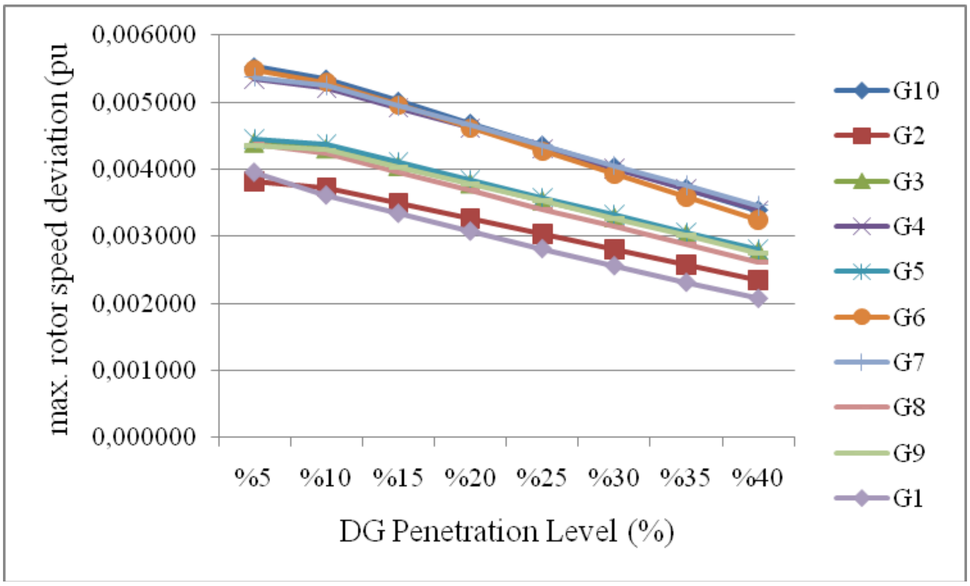

Figure 5.22: Max. rotor speed deviation of each centralized generator when DG is connected as constant PQ source for fault clearing durations 150 ms

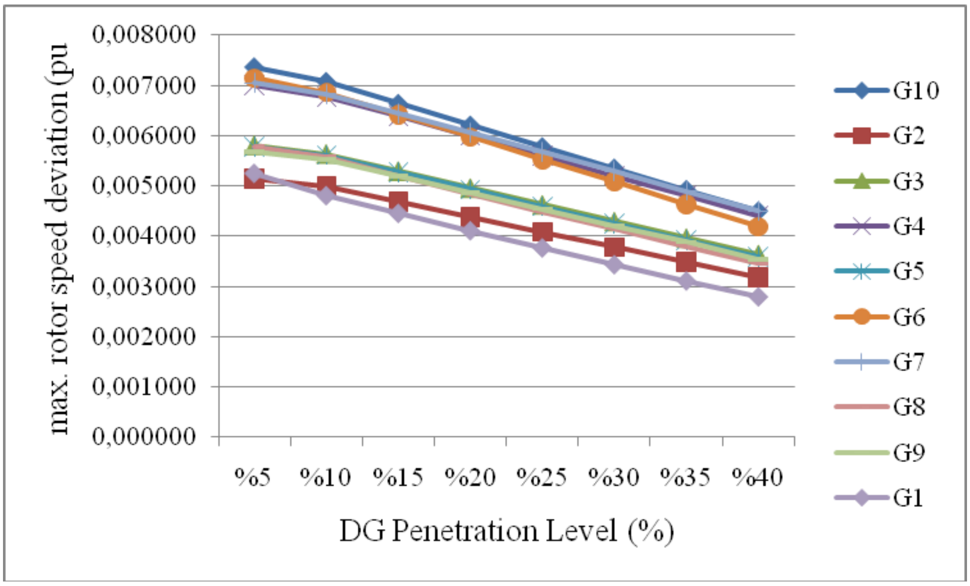

Figure 5.23: Max. rotor speed deviation of each centralized generator when DG is connected as constant PQ source for fault clearing durations 200 ms

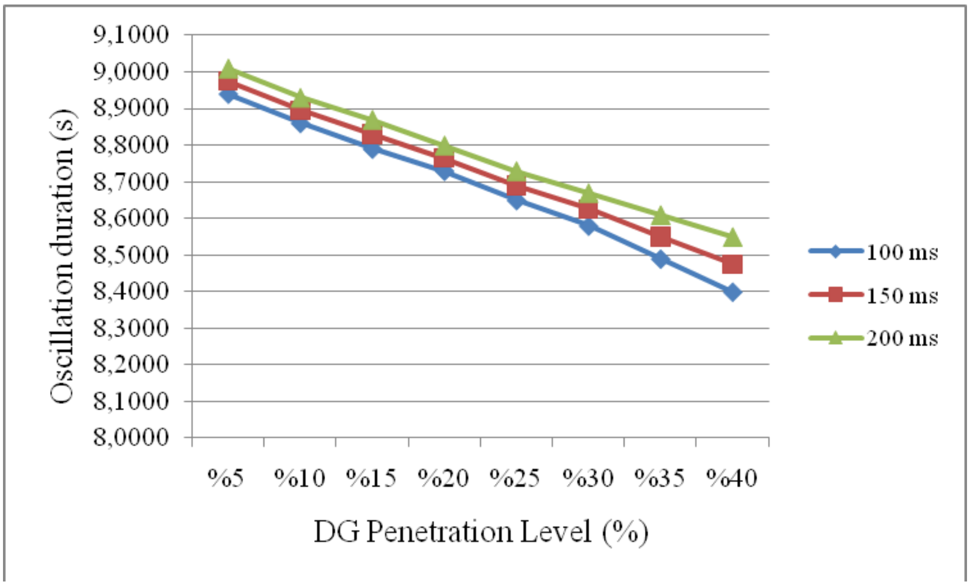

Figure 5.24: Worst value of oscillation duration of centralized generators when DG is connected as constant PQ source for fault clearing durations 100 ms, 150 ms and 200 ms.

5.3 Comparison of Impacts of Different DG Technologies on Power System Transient Stability

In the previous part, the effects of different DG technologies on the power system transient stability are investigated separately. It is focused on the response of the system to the increasing penetration of DG for each technology individually. This part aims to bring a different point of view to the topic through a comparison among the stability indicators for different penetration levels. For each fault duration (100 ms, 150 ms, 200 ms), a table shows the max rotor speed deviation and the oscillation duration of CG for the implementation of different DG technologies (induction generators, synchronous generators with and without voltage and frequency control) and different penetration levels.

In the left columns of tables, the DG penetration level is indicated. In the second rows, the DG technologies are indicated. In the first rows of each penetration level for each DG technology, the left upper cells indicate max. rotor speed deviation and the right upper cells indicate oscillation duration. The bottom left and right cells indicate the relative change of the max. rotor speed deviation (left cells) and the oscillation duration (right cells) to previous penetration level in per cent.

Table-5.1: Comparison of max. rotor speed deviation and oscillation duration of CG when different DG Technologies are coupled with increasing DG penetration level for fault duration 100 ms.

DG Level%	Max. Rotor speed deviation 10^{-3} (pu)-Oscillation Duration (s) and relative change (%)					
	INDUCTION GENERATOR		SYNCHRONOUS GENERATOR WITH VOLTAGE AND FREQUENCY CONTROL		SYNCHRONOUS GENERATOR WITHOUT VOLTAGE AND FREQUENCY CONTROL	
0	2.840	9.670	2.840	9.670	2.840	9.670
	0%	0%	0%	0%	0%	0%
5	2.286	15.330	2.652	9.460	2.611	15.750
	-19.51%	58.53%	-6.62%	-2.17%	-8.06%	62.88%
10	2.254	14.590	2.558	8.500	2.548	13.950
	-1.40%	-4.83%	-3.54%	-10.15%	-2.41%	-11.43%
15	2.223	14.530	2.401	8.420	2.401	13.880
	-1.38%	-0.41%	-6.14%	-0.94%	-5.77%	-0.50%
20	2.177	13.570	2.244	7.330	2.244	13.830
	-2.07%	-6.61%	-6.54%	-12.95%	-6.54%	-0.36%
25	2.117	13.550	2.086	6.390	2.086	13.770
	-2.74%	-0.15%	-7.04%	-12.82%	-7.04%	-0.43%
30	2.149	13.520	1.928	6.310	1.928	12.970
	1.49%	-0.22%	-7.57%	-1.25%	-7.57%	-5.81%
35	2.217	13.500	1.770	6.200	1.770	12.920
	3.18%	-0.15%	-8.20%	-1.74%	-8.20%	-0.39%
40	2.311	13.850	1.611	5.670	1.611	12.880
	4.23%	2.59%	-8.98%	-8.55%	-8.98%	-0.31%

Table 5.2: Comparison of max. rotor speed deviation and oscillation duration of CG when different DG Technologies are coupled with increasing DG penetration level for fault duration 150 ms.

DG Level%	Max. Rotor speed deviation 10^{-3} (pu)-Oscillation Duration (s) and relative change (%)					
	INDUCTION GENERATOR		SYNCHRONOUS GENERATOR WITH VOLTAGE AND FREQUENCY CONTROL		SYNCHRONOUS GENERATOR WITHOUT VOLTAGE AND FREQUENCY CONTROL	
0	4.082	10.600	4.082	10.600	4.082	10.600
	0%	0%	0%	0%	0%	0%
5	3.260	16.390	3.818	9.440	3.777	15.740
	-20.14%	54.62%	-6.47%	-10.94%	-7.47%	48.49%
10	3.172	15.230	3.658	9.240	3.658	14.780
	-2.70%	-7.08%	-4.19%	-2.12%	-3.15%	-6.10%
15	3.129	15.190	3.437	8.450	3.438	13.940
	-1.36%	-0.26%	-6.04%	-8.55%	-6.01%	-5.68%
20	3.066	15.170	3.216	8.400	3.217	14.670
	-2.02%	-0.13%	-6.43%	-0.59%	-6.43%	5.24%
25	2.984	15.120	2.995	8.330	2.996	14.610
	-2.66%	-0.33%	-6.87%	-0.83%	-6.87%	-0.41%
30	2.932	15.090	2.775	7.240	2.775	14.510
	-1.76%	-0.20%	-7.35%	-13.09%	-7.38%	-0.68%
35	3.090	15.030	2.554	7.190	2.554	13.740
	5.41%	-0.40%	-7.96%	-0.69%	-7.96%	-5.31%
40	3.158	15.490	2.332	7.000	2.333	14.790
	2.19%	3.06%	-8.69%	-2.64%	-8.65%	7.64%

Table 5.3: Comparison of max. rotor speed deviation and oscillation duration of CG when different DG Technologies are coupled with increasing DG penetration level for fault duration 200 ms.

DG Level%	Max. Rotor speed deviation 10^{-3} (pu)-Oscillation Duration (s) and relative change (%)					
	INDUCTION GENERATOR		SYNCHRONOUS GENERATOR WITH VOLTAGE AND FREQUENCY CONTROL		SYNCHRONOUS GENERATOR WITHOUT VOLTAGE AND FREQUENCY CONTROL	
0	5.529	11.030	5.529	11.030	5.529	11.030
	0%	0%	0%	0%	0%	0%
5	4.100	18.050	4.831	9.480	4.790	17.500
	-25.85%	63.65%	-12.62%	-14.05%	-13.37%	58.66%
10	3.961	16.320	4.614	9.350	4.615	15.610
	-3.39%	-9.58%	-4.49%	-1.37%	-3.65%	-10.80%
15	3.906	15.290	4.339	9.210	4.340	15.540
	-1.39%	-6.31%	-5.96%	-1.50%	-5.96%	-0.45%
20	3.827	15.950	4.065	8.430	4.067	15.440
	-2.03%	4.32%	-6.31%	-8.47%	-6.29%	-0.64%
25	3.726	16.220	3.793	8.370	3.795	14.690
	-2.64%	1.69%	-6.69%	-0.71%	-6.69%	-4.86%
30	3.661	16.180	3.522	8.280	3.524	14.620
	-1.74%	-0.25%	-7.14%	-1.08%	-7.14%	-0.48%
35	3.718	16.150	3.251	7.260	3.254	14.570
	1.55%	-0.19%	-7.69%	-12.32%	-7.66%	-0.34%
40	3.782	17.120	2.981	7.220	2.984	14.500
	1.72%	6.01%	-8.31%	-0.55%	-8.30%	-0.48%

Some of the results obtained from the comparison tables are similar to the ones in part 5.2 and some of them are gained with different point of view. The results can be listed as follows;

- As it is expected, in the base case, the max. rotor speed deviation and the oscillation duration are increasing when the fault duration is getting longer.

- Generally, the implementation of DG to the system leads to an improvement of the max. rotor speed deviation of the centralized generators for all fault durations. Yet a generalization cannot be deduced for the oscillation duration.

- Firstly, the connection of the induction generators as DG leads to more improvement of the max. rotor speed deviation than the case when controlled or uncontrolled synchronous generators are implemented as DG. However, this is reversing with the increase in penetration level.

- For 100 ms fault duration, the penetration of induction generators up to 25% level, it is resulted in improvements in the max. rotor speed deviation of the system but further penetrations cause certain decrease in the max. rotor speed deviation. This is almost the same for 150 ms and 200 ms fault durations. Only the difference is that the implementation of the induction generators leads to the improvement of max. rotor speed deviation up to 30% penetration level and then cause a decrement of the indicator. In spite of this, the max. rotor speed deviation value at each penetration level is better than the ones in the base case.

- When the synchronous generators (with or without voltage and frequency control) are coupled to the system as DG, the max. rotor speed deviation of the centralized generators show improvement with increasing penetration level (and) with the increasing percentage compare to the previous penetration level except for 10% penetration level.

- Max. rotor speed deviation is almost the same for the cases when the synchronous generators with and without voltage and frequency control are used as DG for the same fault duration and same penetration level. The positive impact of implementing controlled synchronous generator is seen on the oscillation duration. Oscillation duration is much better when the controlled synchronous generators are implemented. In the controlled case, oscillation duration leads to an improvement starting from 5% penetration level and up to 40%. However, implementation of the uncontrolled synchronous generators lowers the stability margin of the system by long oscillations. At the lower penetration levels, oscillation durations are close to the case with the induction generators but it differs with further penetration.

- It can be concluded that when DG is equipped with frequency and voltage control, it leads to improvement in the stability margin of the system by decreasing both max. rotor speed deviation and oscillation duration of CG, but the implementation of uncontrolled DG causes more complex result. The effect varies depending on the connected technology and the penetration level.

5.4 Impacts of DG on Critical Clearing Time (CCT) for Different Penetration Levels

In parts 5.2 and 5.3, impacts of the different DG technologies on stability for the different penetration levels and fault durations have been investigated respectively. Therefore, at each simulation scenarios, only one type of DG technologies is implemented to the each load bus. On the contrary in this part, a mixture of the different technologies is coupled to the specified load buses and variations of the CCT are observed while the penetration of DG is increasing. The main focus of this part is on the response of the system when different DG technologies are implemented at the same time instead of respectively.

Again, New England (IEEE-39 bus) test system is used for simulations. The original state (no coupled DG) of the system is taken as base case and then three different DG technologies are coupled to the six different locations of the system. DG is added to the related load buses as described in part 4.4. Synchronous generators with control are coupled to the buses 4 and 20, synchronous generators without control are added to the buses 8 and 16, and at buses 24 and 28, induction generators are connected. Extended system is depicted in figure 5.25. In order to increase the penetration level first scenario which is described in part 5.1 is applied with the details as follows. Generation of CG is kept constant, load of the buses where DG is added are increased accordingly the projected penetration level and the increased load demand is supplied by the related DG. The penetration level is increased from 5% up to 30% which is equal to around 43% load increases. A three phase permanent fault is applied to between the line 15-16 and CCT for different scenarios are obtained by tripping the line 15-16.

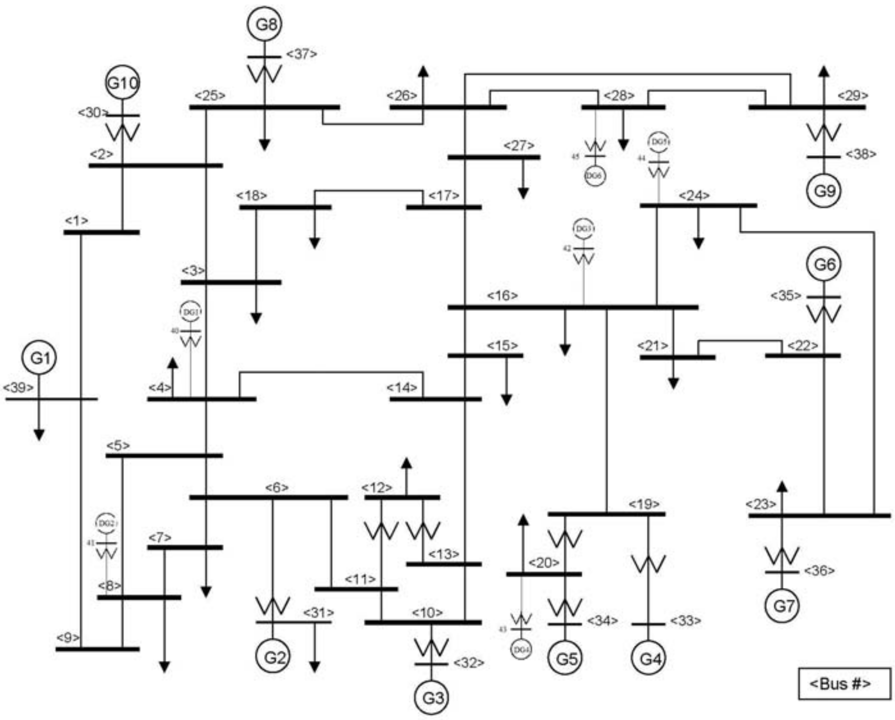

Figure 5.25: Extended New England Test System

While the system is stable with a clearing time of 0.62 s in the base case, G6 and G7 go unstable with a clearing time of 0.63 s. However, implementation of DG with a

5% penetration level leads to improvement of CCT of the system. The system goes unstable when clearing time is 0.69 s.

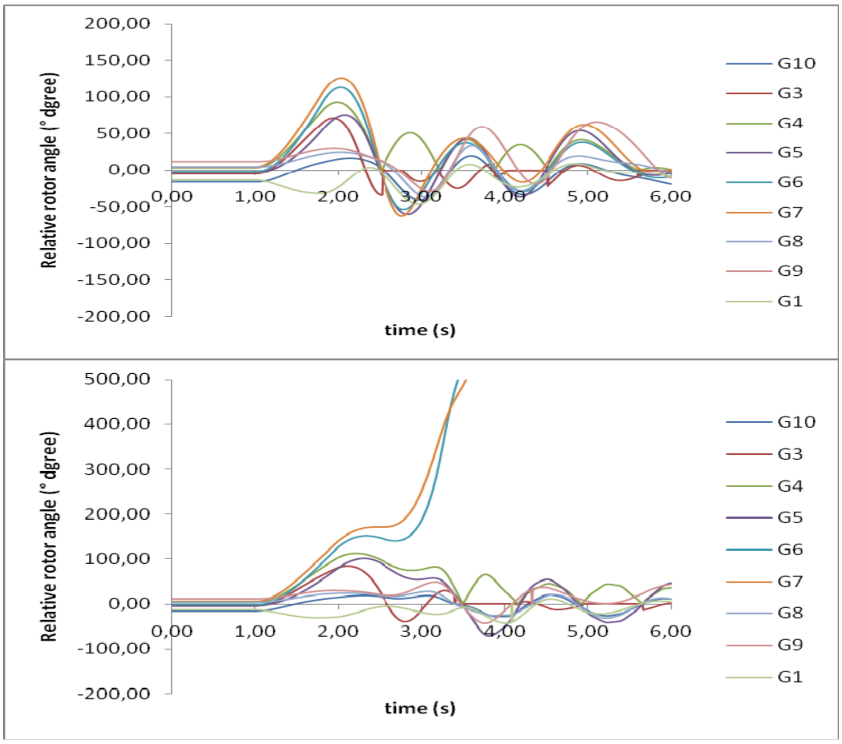

Figure 5.26: Relative rotor angles for the base case with t_{ct}=0.62 s (top) and t_{ct}=0.63 s (bottom)

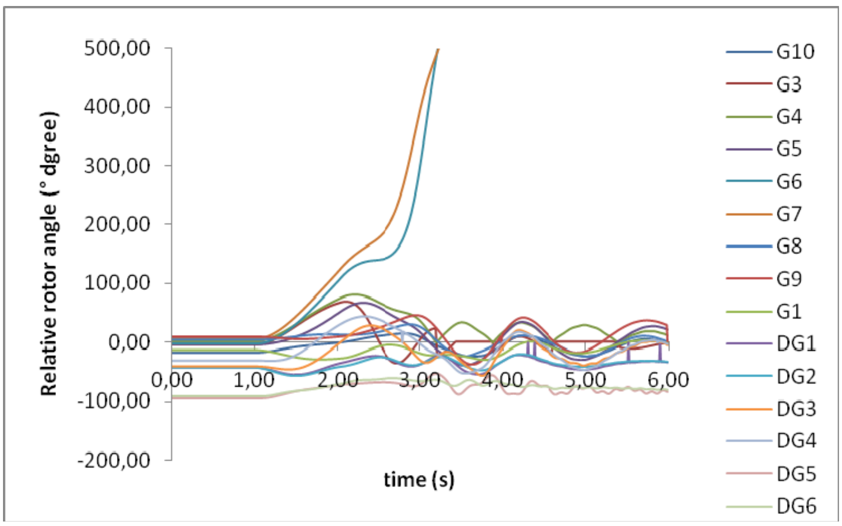

Figure 5.27: Relative rotor angles for the 5% penetration level with t_{ct}=0.69 s

CCT of the system is extended compare to base case along with increasing penetration up to 20%. However, implementation of DG with a 30% penetration leads to a sudden decrease in CCT.

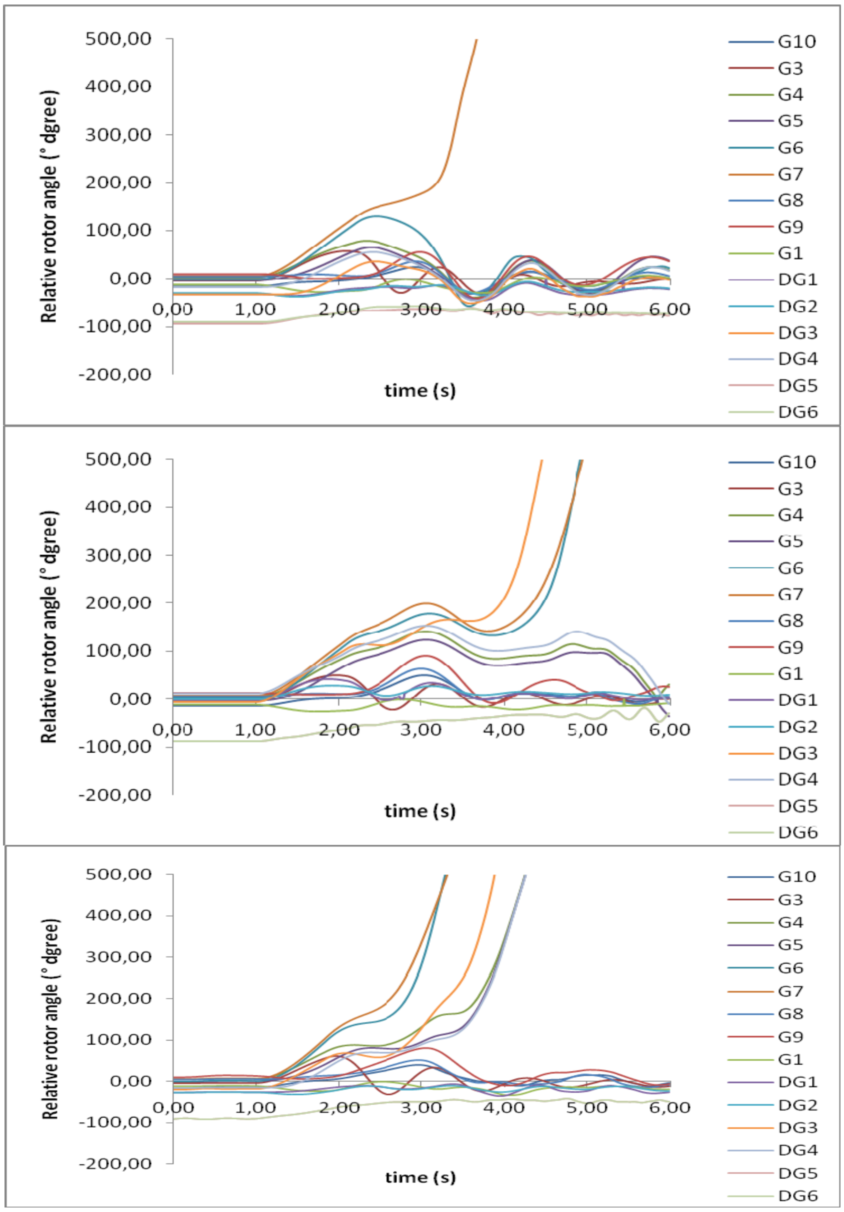

Figure 5.28: Relative rotor angles for the 10% penetration level (top) with t_{ct}=0.79 s, Relative rotor angles for the 20% penetration level (middle) with t_{ct}=0.73 s, Relative rotor angles for the 30% penetration level (bottom) with t_{ct}=0.57 s.

G7 goes unstable for all penetration levels including base case. G6, also show similar tendency except at 10% penetration level. G6 and G7 are weakest machines in the base case and they are continued to go unstable with increasing penetration. In the simulation results of the parts 5.2 and 5.3, G6 and G7 show worst rotor speed deviation value after G4. Implementation of DG closer to their buses can be prevented them to be the weakest generators in the system and this shows that addition of DG to a load bus leads to a some improvement.

Penetration of DG leads to improvement on CCT up to 10% level and this is the strongest system in terms of CCT. However further penetration increases number of unstable generators in the system and leads to decrease in CCT. At 30% penetration level, CCT drops below CCT at base case and six generators go unstable. It can be concluded that positive impacts of DG is appeared as long as its penetration is kept at reasonable levels. Beyond that, its positive impacts are oberved up to the 20% penetration level and further penetration results is decrease of stability margin.

Table 5.4: Critical clearing time and unstable generators for different penetration levels.

Penetration level (%)	CCT (s)	Unstable Generators
Base Case	0.62	G6,G7
5	0.68	G6,G7
10	0.78	G7
20	0.72	G6,G7,DG3
30	0.56	G4,G5,G6,G7,DG3,DG4

5.5 Impacts of DG on Critical Clearing Time (CCT) for Connection to the System with Different Impedance Values

Same simulation scenarios are used with part 5.4 except total value of X_{T-DG} and X_{L-DG}. In the previous part, total value of X_{T-DG} and X_{L-DG} is set to a constant value, 0.05 pu on 100 MVA base. In this part, to investigate the impact of the impedance of the connection of the DG to the system while penetration is increasing, the total value of X_{T-DG} and X_{L-DG} is changed at each penetration level and R_{L-DG} is neglected (Fig. 4-8) at all penetration levels. At 5% and 10% penetration level, total impedance value is set to 0.32 pu on 100 MVA base, at 20% and 30% penetration level total impedance value is set to 0.24 pu and 0.12 pu on the same system base, respectively.

At 5% penetration level, the increased impedance of the connection of the DG to the system results in a slightly increase of CCT compare to the base case and only unstable generator is G7. With increasing penetration up to 10% level, CCT of the system continues to increase to 0.68 s and again only unstable generator is G7. However when the penetration of the DG is increased, stability margin of the system starts to decrease. At 20% and 30% penetration level, CCT is 0.60 s and 0.54 s, respectively. At both penetration levels, CCT is lower than the CCT in the base case.

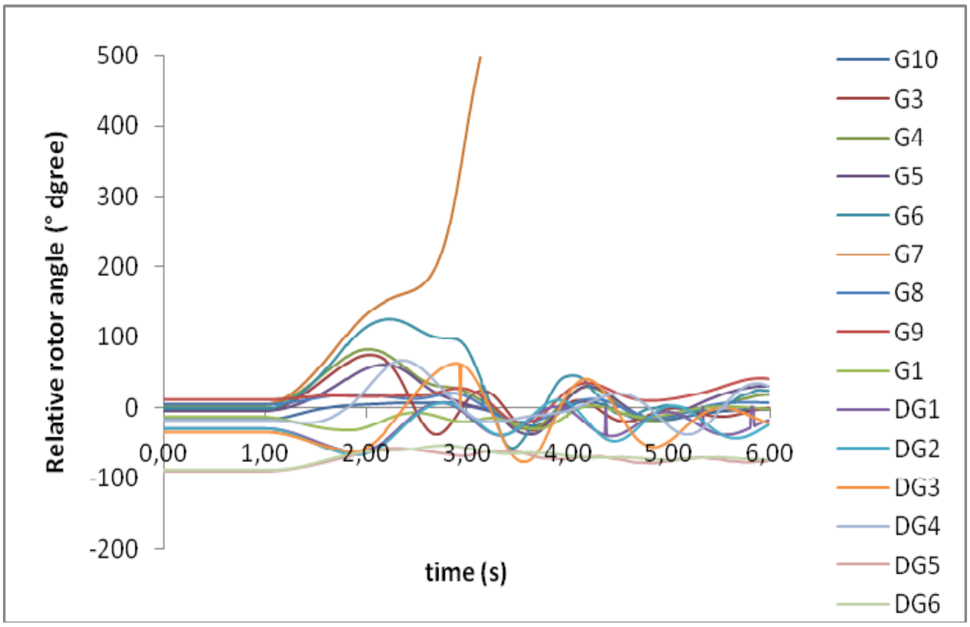

Figure 5.29: Relative rotor angles for the 5% penetration level with t_{ct}=0.64 s

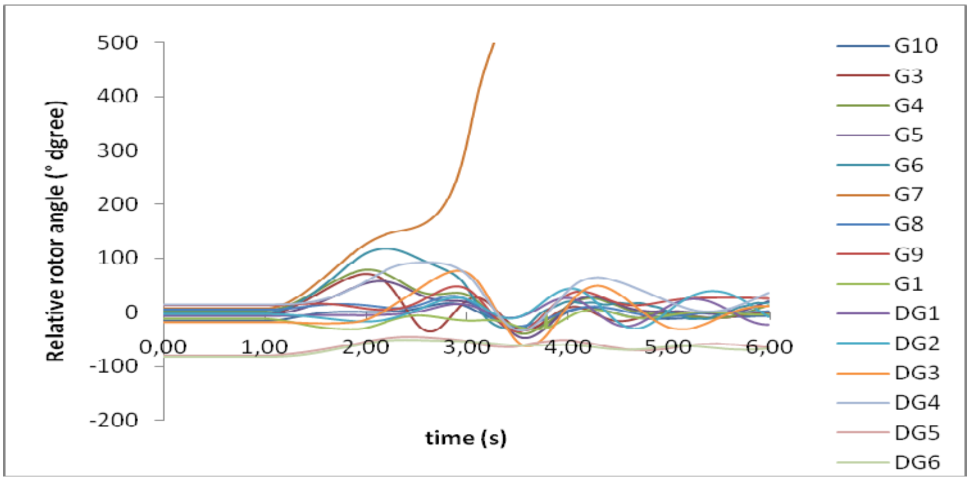

Figure 5.30: Relative rotor angles for the 10% penetration level with t_{ct}=0.69 s

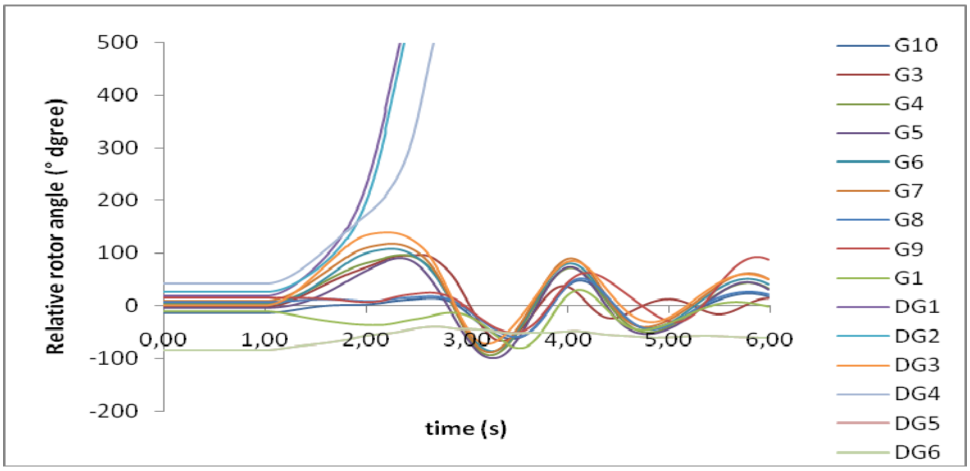

Figure 5.31: Relative rotor angles for the 20% penetration level with t_{ct}=0.61 s

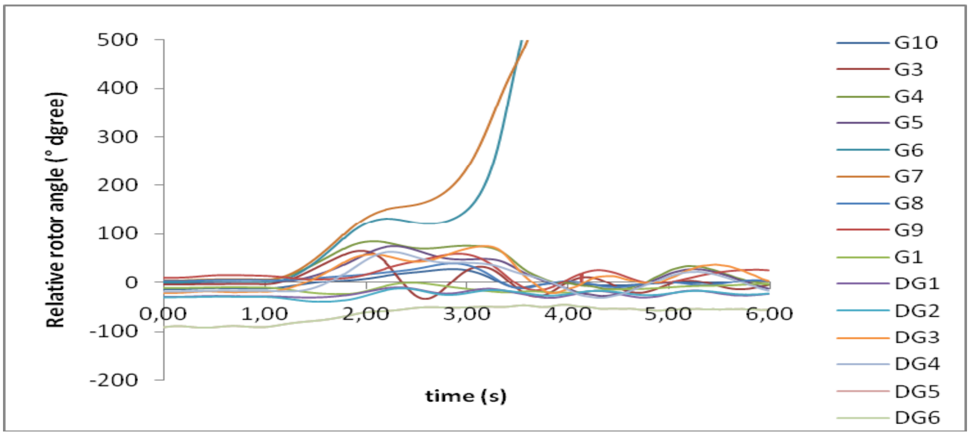

Figure 5.32: Relative rotor angles for the 30% penetration level with t_{ct}=0.55 s

Summary of the results reached when the connection of the distributed generators to the system is made with different impedance values are shown in table 5.5. Generally, the results show that system stability improves up to 10% penetration level and decreases with further penetration. When the results are compared to the ones in part 5.4, the obtained inferences are summarized as follows;

- The increasing impedance of the connection of the generators to the system leads to a decrease in the stability of the system. So, critical clearing times obtained in this case are lower compare to the times in the constant impedance case for all penetration levels.

- Even the tendency of the variation of CCT with increasing penetration level is similar in both cases (in both cases, CCT of the system improves up to 10% penetration level and then starts to decrease with further penetration), critical clearing times are more close to each other in the different impedance case. This can be explained as follows; when the connection of the DG to system is made with constant impedance for all penetration levels, the only factor on the CCT is penetration level. So, CCT increases up to certain levels and then decreases due to negative impact of high-level penetration of DG. However, when the connection impedance of DG to the system is high at low penetration levels and low at high penetration levels, CCT is affected positively from implementation of DG at low penetration levels and negatively at high penetration levels and on the contrary CCT is affected negatively when the connection made through high impedance and positively when the connection is made through low impedance. So, variation of CCT with increasing penetration is closer due to this neutralizing effect of penetration level and impedance parameters on each other.

- When the CCT is reached a lower value than base case value at 30% penetration level in the constant impedance case, this time at 20% level CCT of the system is reached a lower value compare to the one in the base case.

This can be obtained due to negative impact of connection of generators with high impedance on the system stability.

Table 5.5: Critical clearing time and unstable generators for connection to the system with different impedance values.

Penetration level (%)	CCT (s)	Unstable Generators
Base Case	0.62	G6,G7
5	0.63	G7
10	0.68	G7
20	0.60	DG1,DG2,DG4
30	0.54	G6,G7

CHAPTER 6

CONCLUSION

6.1 Conclusion

Nowadays, electricity generation from small-generation units which are connected to the system at the distribution level is becoming popular all over the world. This generation units are referred to as "distributed generation", "embedded generation" or "dispersed generation" in the literature. They influence the power system at both distribution and transmission level positively as well as negatively. Although the main impacts of them are on the distribution systems, they have started to influence the transmission system as the penetration of these units has been increased. In this study, the impacts of DG on the transmission system have been studied with a focus on rotor angle stability.

Well-known New England (IEEE-39 bus) test system has been used in this study. Four different DG technologies have been connected to the system. Dynamic models of the synchronous generators with grid voltage and frequency control, the synchronous generators without grid voltage and frequency control and the induction generators are implemented to the system as DG. To see the results when they are added to the system as constant active and reactive power generators without considering their detailed models, distributed generators are coupled to the system also as negative load.

Simulation scenarios have also been developed to assess also the impacts of penetration level of DG on the transmission system. Simulations have been run on the basis of these scenarios.

In the parts 5.2 and 5.3, only one DG technology is implemented to the each load buses and two stability indicators (maximum rotor speed deviation and maximum rotor angle oscillation duration) have been observed during each simulation. The aim of these parts is to assess the impacts of the different DG technologies on system rotor angle stability for the different fault durations while penetration level is increasing. The results obtained from the simulations can be summarized as follows,

- When DG is added to the system as constant PQ-source, both of the stability indicators consistently improve with the increasing penetration level. This can be explained as follows. The heavier transmission lines leads to decrease in stability margin of the system. As the implementation of DG is a natural way of limiting the power flows over the transmission lines, this is the expected result for this case in which the dynamic models of DG are not used.

- Addition of the synchronous generators with control strengthens the system in terms of the rotor speed deviation and oscillation duration of CG. However, the improvement on the oscillation duration cannot be seen as clear as the improvement on rotor speed deviation. For all fault durations and penetration levels, G4 is the weakest generator of the system. This can be due to absence of the distributed generators to any closed buses of this generator.

- While the results of max. rotor speed deviation of the uncontrolled synchronous generators case is almost same as the controlled case, oscillation duration shows different behavior in the uncontrolled case. Oscillation duration of CG fluctuates with the increasing penetration level for all fault durations. This can be by reason of the increasing the installed capacity of the uncontrolled generators while the generation from generators with controlled equipment is decreasing.

- By the implementation of the induction generators, rotor speed deviations of the some generators are affected positively while the some of them are affected negatively. Implementation of the induction generators leads to growth of max. rotor speed deviation of G3 and G10. This can be explained as follows. The effect of the induction generators on stability depends on their distance to the centralized synchronous generators. If they are located near to the synchronous generators, they lead to the slow down of the speed of the synchronous generators by decreasing the slip frequency and generated power. However, when they are placed with a large distance, they lead to a faster increase in rotor speed by increasing the reactive power demand and by lowering the terminal voltage due to speeding up during fault. Nonetheless, they do not change the stability margin of the system much, probably due to the opposite effects of near and remote applications.

- Although different technologies show different behavior at different penetration levels and for different fault durations, max. rotor speed deviations of them are better than the base case for all the penetration levels and the fault durations. However it is not possible to conclude similarly for the oscillation duration. Only when the synchronous generators with voltage and frequency control are implemented, DG technologies have better oscillation durations than the base case. Implementation of uncontrolled distributed generators lowers the stability margin of the system by long oscillations. It can be concluded that to increase the stability margin of the system in every aspect, the ratio of the controlled generation units in the system should not be as decreased to certain levels in per cent.

In part 5.4 and 5.5, CCT variation of the system has been investigated for different penetration levels and for different impedance parameters of connection of DG to the system when mixture of the DG technologies is added to the system. Three different types of generators (uncontrolled and controlled synchronous generator, induction generator) are added to the six load buses at the same simulation scenario and how the stability margin of the system is influenced from the penetration of DG and from impedance variation is observed. The results obtained the simulations can be summarized as below;

- Although G6 and G7 are not the weakest generators in the simulations of the parts 5.2 and 5.3, they are the unstable machines for nearly all penetration levels (except at 10% level which has the highest CCT, G7 is the only unstable machine) in the part 5.4. This can be explained as follows; while distributed generators are implemented to the closer buses of G6 and G7 in the parts 5.2 and 5.3, in the part 5.4 distributed generators are located further relatively.
- Increasing impedance parameters of the connection of DG to the system leads to a decrease in the stability margin of the system. When the critical clearing times are compared between constant impedance case and changing impedance case, at each penetration level critical clearing times are lower at the constant impedance case.
- At constant impedance case penetration of DG up to 20% level leads to improvement on the stability margin of the system by increasing CCT. For changing impedance parameters case, improvement is observed penetration of DG up to 10% level. However, further penetration leads to a decrease in CCT at both cases. Same results are observed for number of unstable generators. A sudden increase is seen on the number of the unstable generators at 30% penetration level. It can be concluded that DG is not a concern to the system stability as long as the penetration of the DG is kept at reasonable levels.

6.2 Future Works

Implementation of DG is effected to the system as a whole. In this study, the focus is specifically on rotor angle stability. But it could be considered that increased installed capacity of DG has also impacts on voltage stability. The study could be extended by means of including voltage stability.

Connection of distributed generators from distribution system to transmission system has been provided by including effects of transformer and line impedances to the system instead of detailed model of distribution system. These impedances have been set to a constant value during all simulation scenarios. But by changing the value of these impedances, impacts of connection distance of DG on power system dynamics could also be observed.

Impacts of indirectly connected (via power electronic converters) DG to the grid have been excluded in this study. Even their behaviors are similar to constant PQ-sources, it is needed to be including their protection schemes to the simulations to get realistic results. DG technologies connected to the grid via power electronic converters could be added.

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APPENDIX A

NEW ENGLAND (IEEE-39 BUS) TEST SYSTEM DATA

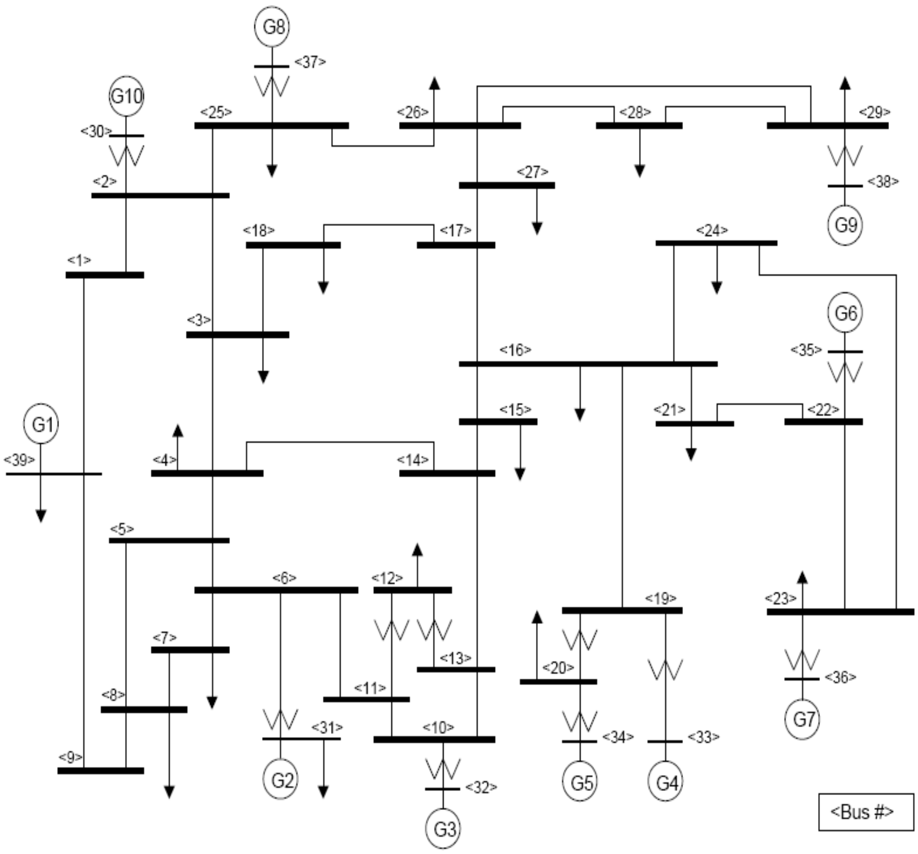

Figure A.1: Single Diagram of New England (IEEE 39-bus) test system

Table A.1 Bus data of New England (IEEE 39-bus) test system

Bus Number	Volts (pu)	Load (MW)	Load (MVAR)	Generation (MW)
1	-	0.0	0.0	-
2	-	0.0	0.0	-
3	-	322.0	2.4	-
4	-	500.0	184.0	-
5	-	0.0	0.0	-
6	-	0.0	0.0	-
7	-	233.8	84.0	-
8	-	522.0	176.0	-
9	-	0.0	0.0	-
10	-	0.0	0.0	-
11	-	0.0	0.0	-
12	-	8.5	88.0	-
13	-	0.0	0.0	-
14	-	0.0	0.0	-
15	-	320.0	153.0	-
16	-	329.4	32.3	-
17	-	0.0	0.0	-
18	-	158.0	30.0	-
19	-	0.0	0.0	-
20	-	628.0	103.0	-
21	-	274.0	115.0	-
22	-	0.0	0.0	-
23	-	247.5	84.6	-
24	-	308.6	-92.2	-
25	-	224.0	47.2	-
26	-	139.0	17.0	-
27	-	281.0	75.5	-
28	-	206.0	27.6	-
29	-	283.5	26.9	-
30	1.0475	0.0	0.0	250.0
31	0.9820	9.2	4.6	-
32	0.9831	0.0	0.0	650.0
33	0.9972	0.0	0.0	632.0
34	1.0123	0.0	0.0	508.0
35	1.0493	0.0	0.0	650.0
36	1.0635	0.0	0.0	560.0
37	1.0278	0.0	0.0	540.0
38	1.0265	0.0	0.0	830.0
39	1.0300	1104.0	250.0	1000.0

Table A.2: Line data of New England (IEEE 39-bus) test system

From Bus	To Bus	Resistance	Reactance	Susceptance	Transformer
1	2	0.0035	0.0411	0.6987	0.0000
1	39	0.0010	0.0250	0.7500	0.0000
2	3	0.0013	0.0151	0.2572	0.0000
2	25	0.0070	0.0086	0.1460	0.0000
3	4	0.0013	0.0213	0.2214	0.0000
3	18	0.0011	0.0133	0.2138	0.0000
4	5	0.0008	0.0128	0.1342	0.0000
4	14	0.0008	0.0129	0.1382	0.0000
5	6	0.0002	0.0026	0.0434	0.0000
5	8	0.0008	0.0112	0.1476	0.0000
6	7	0.0006	0.0092	0.1130	0.0000
6	11	0.0007	0.0082	0.1389	0.0000
7	8	0.0004	0.0046	0.0780	0.0000
8	9	0.0023	0.0363	0.3804	0.0000
9	39	0.0010	0.0250	1.2000	0.0000
10	11	0.0004	0.0043	0.0729	0.0000
10	13	0.0004	0.0043	0.0729	0.0000
13	14	0.0009	0.0101	0.1723	0.0000
14	15	0.0018	0.0217	0.3660	0.0000
15	16	0.0009	0.0094	0.1710	0.0000
16	17	0.0007	0.0089	0.1342	0.0000
16	19	0.0016	0.0195	0.3040	0.0000
16	21	0.0008	0.0135	0.2548	0.0000
16	24	0.0003	0.0059	0.0680	0.0000
17	18	0.0007	0.0082	0.1319	0.0000
17	27	0.0013	0.0173	0.3216	0.0000
21	22	0.0008	0.0140	0.2565	0.0000
22	23	0.0006	0.0096	0.1846	0.0000
23	24	0.0022	0.0350	0.3610	0.0000
25	26	0.0032	0.0323	0.5130	0.0000
26	27	0.0014	0.0147	0.2396	0.0000
26	28	0.0043	0.0474	0.7802	0.0000
26	29	0.0057	0.0625	1.0290	0.0000
28	29	0.0014	0.0151	0.2490	0.0000
2	30	0.0000	0.0181	0.0000	1.0250
6	31	0.0000	0.0250	0.0000	1.0700
10	32	0.0000	0.0200	0.0000	1.0700
11	12	0.0016	0.0435	0.0000	1.0060
12	13	0.0016	0.0435	0.0000	1.0060
19	20	0.0007	0.0138	0.0000	1.0600
19	33	0.0007	0.0142	0.0000	1.0700
20	34	0.0009	0.0180	0.0000	1.0090
22	35	0.0000	0.0143	0.0000	1.0250
23	36	0.0005	0.0272	0.0000	1.0000
25	37	0.0006	0.0232	0.0000	1.0250
29	38	0.0008	0.0156	0.0000	1.0250

APPENDIX B

NEW ENGLAND (IEEE-39 BUS) TEST SYSTEM DYNAMIC DATA

Table B.1: Model data of induction generators

T'	**T''**	**H**	**X**	**X'**	**X"**
0.98	0	3	0.31	0.018	0
Xl	**E1**	**S(E1)**	**E2**	**S(E2)**	**0.switch**
0.01	1	0	1.2	0	0

Table B.2: Model data of synchronous generators

T'do	**T''do**	**T'qo**	**T''qo**	**H**	**D**
7	0.03	0.7	0.04	5	0
Xd	**Xq**	**X'd**	**X'q**	**X"d=X"q**	**Xl**
1.5	1.5	0.6	0.6	0.2	0.3

Table B.3: Governer model data for synchronous generator

R	**T1 (>0) (sec)**	**V MAX**	**V MIN**	**T2 (sec)**	**T3 (>0) (sec)**	**Dt**
0.05	0.05	0.91	0	2.1	7	0

Table B.4: Excitation system model data for synchronous generator

TR	KA	TA (sec)	TB (sec)	TC	VRMAX or	VRMIN	KE or zero
0	5	0.06	0	0	5	-5	-0.05
TE (> 0)	**KF**	**TF1 (> 0)**	**Switch**	**E1**	**SE(E1)**	**E2**	**SE(E2)**
0.25	0.04	1	0.00	1.7	0.5	3	2

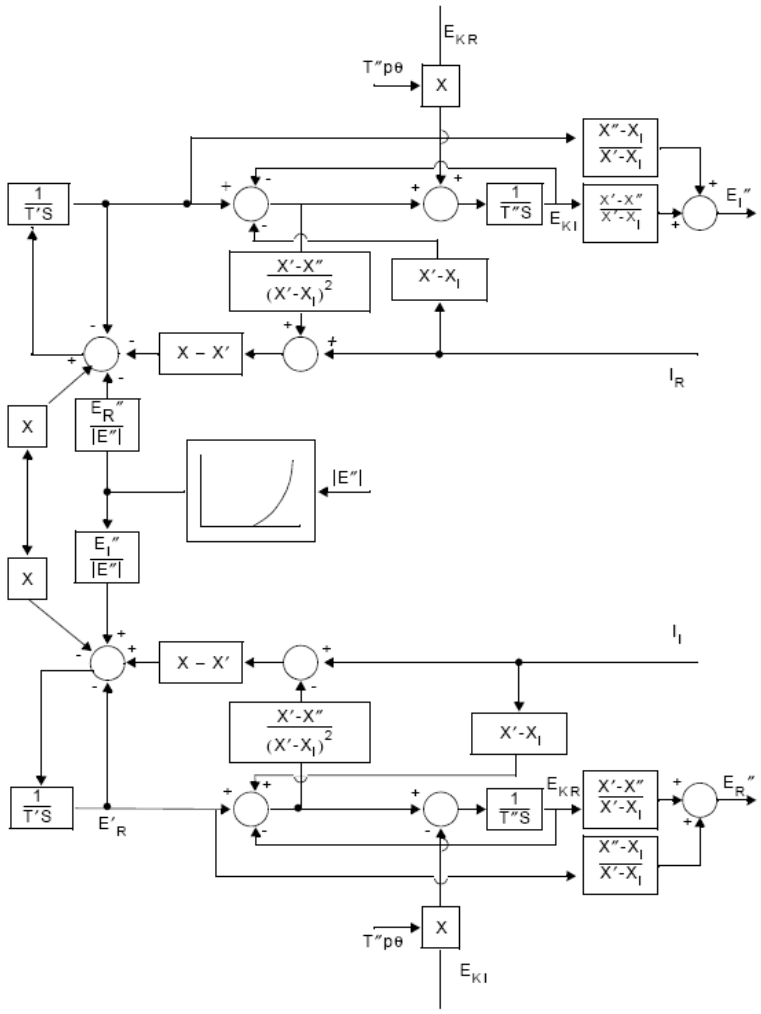

Figure B.1: Induction generator model block diagram [26]

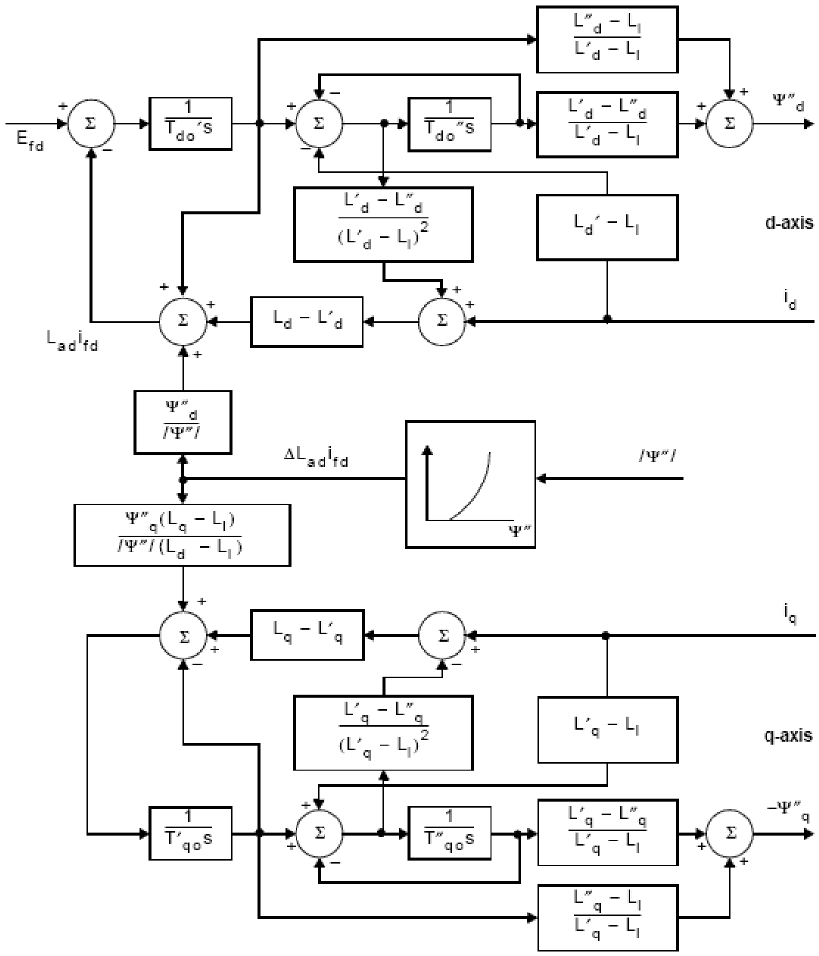

Figure B.2: Synchronous generator model block diagram [26]

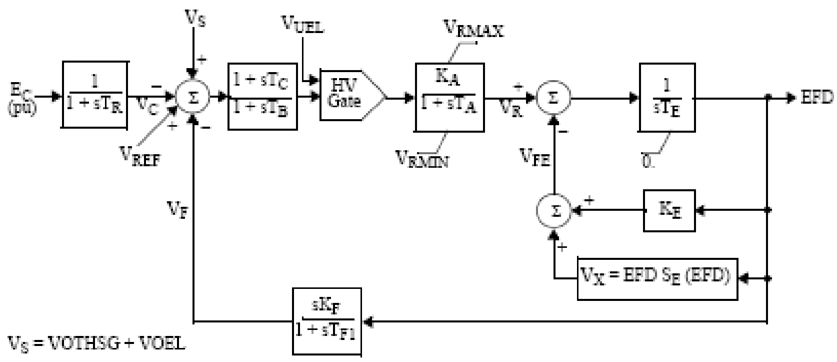

Figure B.3: Excitation model block diagram [26]

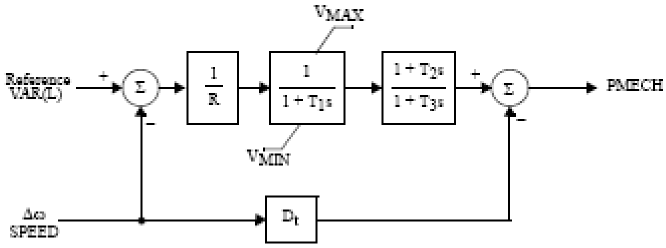

Figure B.4: Governer model block diagram [26]

APPENDIX C

CRITICAL CLEARING TIME AND ANGLE

C.1 Power –Angle Equation

A model of a generator operating under steady-state conditions is given in Fig C-1.

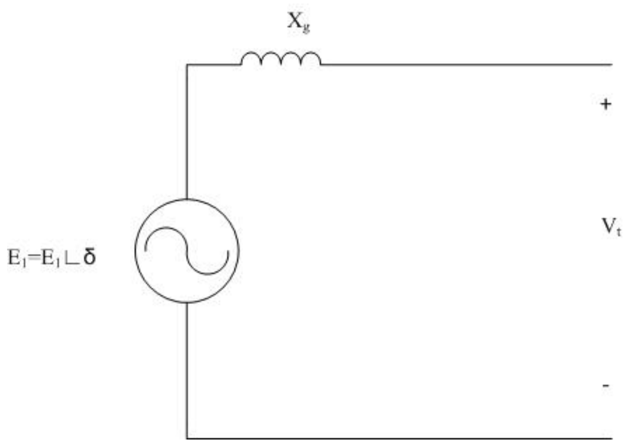

Figure C.1: Simplified synchronous generator model

The generator current is;

$$I = \frac{E_1 e^{j\delta} - V_t}{jX_g} \quad \text{(C-1)}$$

Where E_1 is excitation voltage, V_t is the terminal voltage, δ is the power angle and X_g is the positive-sequence synchronous reactance. The complex power delivered by the generator is;

$$S = P + jQ = V_t I^* = V_t \left(\frac{E_1 e^{-j\delta} - V_t}{-jX_g}\right)$$
$$= \frac{V_t E_1 (j\cos\delta + \sin\delta) - jV_t^2}{X_g} \qquad \text{(C-2)}$$

Then the real and reactive power delivered is as follows;

$$P = \mathrm{Re}(S) = \frac{V_t E_1}{X_g}\sin\delta \qquad \text{(C-3)}$$

$$Q = \mathrm{Im}(S) = \frac{V_t}{X_g}(E_1\cos\delta - V_t) \qquad \text{(C-4)}$$

If a generator connects to the bus (Fig C-2), the power-angle relation becomes;

$$P_e = \frac{E_1 V_1}{X_{eq}}\sin\delta = P_{\max}\sin\delta \qquad \text{(C-5)}$$

Where $X_{eq} = X_g + X_l$ and $P_{max} = \frac{E_1 V_1}{X_{eq}}$

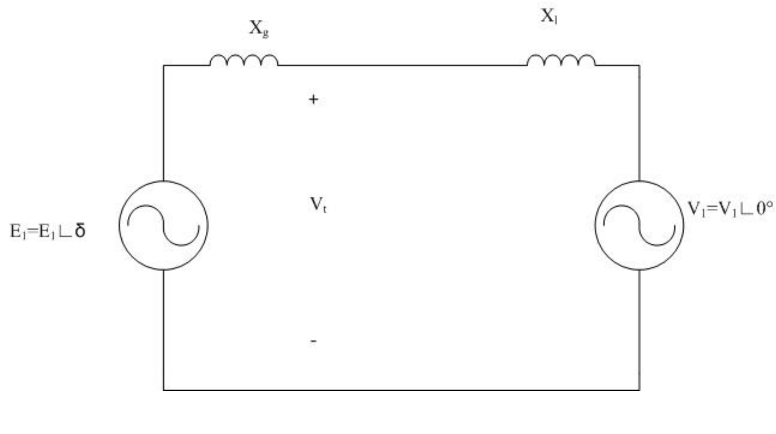

Figure C.2: Two machine system

C.2 the Swing Equation

If the torque caused by friction, windage and core loss in a machine is disregarded any difference between the shaft torque and the electromagnetic torque developed must cause acceleration or deceleration of the machine. If T_s represents shaft torque and T_e is electromagnetic torque, and if these values of torque are considered positive for a generator, the torque causing acceleration is [29];

$$T_a=T_s-T_e \tag{C-6}$$

A similar equation holds for accelerating power,

$$P_a=P_s-P_e \tag{C-7}$$

Where P_a is the shaft power and P_e is the electric power developed for a generator.

Since power is equal to torque times angular velocity,

$$P_a=T_a w=I\alpha w=M\alpha \tag{C-8}$$

The acceleration α expressed in terms of the angular position θ of the rotor is,

$$\alpha=\frac{d^2\theta}{dt^2} \tag{C-9}$$

Since θ is continually changing with time, it is more convenient to measure angular position with respect a reference axis that is rotating at asynchronous speed. If δ is the angular displacement in electrical degrees from the synchronously rotating reference axis and w_s is synchronous speed in electrical degrees per second [29],

$$\theta= w_s t+\delta \tag{C-10}$$

and taking the derivative again,

$$\frac{d\theta}{dt}=w_s+\frac{d\delta}{dt} \tag{C-11}$$

And taking the derivative again,

$$\frac{d^2\theta}{dt^2} = \frac{d^2\delta}{dt^2} \tag{C-12}$$

From equations (C-8), (C-9) and (C-12), we obtain,

$$M\,\frac{d^2\delta}{dt^2} = P_a = P_s - P_e \tag{C-13}$$

Equation (C-13) is called the swing equation.

C.3 Equal-Area Criterion of Stability

The principle by which stability under transient conditions is determined without solving the swing equation is called the equal-area criterion of stability. The derivation of the equal-area criterion is found in many test books. Figure C-3 shows the most critical stable situation of power-angle curve of a two-machine system for a temporary three-phase fault.

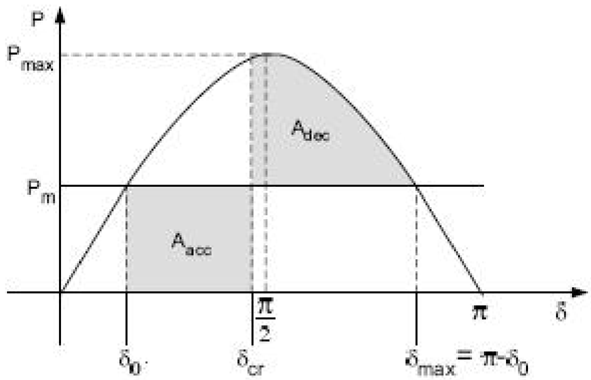

Figure C.3: Power-angle curve

Equal-area criterion suggests that the faulted system is still capable of recovering stability as long as the $A_{acc}<A_{dec}$ is satisfied. The critical case is where;

$$A_{dec} = A_{acc} \tag{C-14}$$

Considering the power-angle curve in figure C-3

$$A_{acc} = \int_{\delta_0}^{\delta_{cr}} P_m d\delta, \quad A_{dec} = \int_{\delta_{cr}}^{\delta_{\max}} (P_{\max} \sin\delta - P_m) d\delta \tag{C-15}$$

By solving C.14 and C.15 together, the critical clearing angle of the system is;

$$\delta_{cr} = \cos^{-1}((\pi - 2\delta_0)\sin\delta_0 - \cos\delta_0) \tag{C-16}$$

Integrating (C-13) twice, provided that $P_a=P_m$ (P_e is zero during the disturbance), at the instant of the critical fault clearing;

$$\delta(t) = \frac{w_s P_m}{4H} t^2{}_{cr} + \delta_o \tag{C-17}$$

The corresponding critical clearing time is obtained as

$$t_{cr} = \sqrt{\frac{4H(\delta_{cr} - \delta_o)}{w_s P_m}} \tag{C-18}$$