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Technical And Economic Impacts Of Distributed Generators And Energy Storage Devices On The Electric Grid

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TECHNICAL AND ECONOMIC IMPACTS OF DISTRIBUTED GENERATORS AND ENERGY STORAGE DEVICES ON THE ELECTRIC GRID

By

Aarthi Asok Kumar

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TECHNICAL AND ECONOMIC IMPACTS OF DISTRIBUTED GENERATORS AND ENERGY STORAGE DEVICES ON THE ELECTRIC GRID

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This research aims at analyzing the impacts of distributed generators and energy storage devices on the transient stability of the grid. Battery and ultra-capacitor have been modeled using Simulink and their impact has been analyzed by connecting them to the small test system built in Simulink using power electronic converters. Transient stability of the test systems has been assessed for different types and locations of faults as well as for different penetration levels of the DGs, with and without the energy storage devices in terms of generator rotor speed deviation, rotor angle and terminal voltage of the DGs. Finally, economic analyses have been carried out for different options of DGs, based on wind, diesel and biomass, along with the energy storage devices. Results indicate that the presence of DGs and storage devices enhances the transient stability of the system in most of the cases.

DEDICATIONS

I would like to dedicate this work to my husband and parents

ACKNOWLEDGEMENTS

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I am thankful to the U.S. Department of Energy (DoE), Sustainable Energy Research Center (SERC) and MSU Cooling, Heating and Power (CHP) Center for providing financial support for this research work. I wish to express my heartfelt thanks to all the graduate students of the power and high voltage group, especially Derrick and Shravana, for their help and comments. Finally, I would like to thank my husband and parents for their love and support during the years of my studies.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Distributed generation is getting a lot of focus in recent years due to various energy and environmental concerns. It can be defined as the process of connecting generators of small capacities close to the loads. Unlike the conventional generators, the distributed generators use both non-renewable and renewable sources of energy to generate electricity. Major technical and economic issues arise when these DG's are interconnected with the electric grid. The technical issues include stability, power quality, protection issues and voltage fluctuations. It has to be noted that certain renewable generators such as wind and solar do not produce power at a constant rate since they are dependent on the natural forces. This makes the use of storage devices very essential.

This research aims at analyzing the impacts of the distributed generator, along with the storage devices, on the transient stability of the grid. Most of the previous work is either done on the transient stability impacts or on the feasibility of using storage devices. Since the storage devices also impact the stability of the grid significantly, this study includes them to analyze the transient stability of an entire system. In addition to the technical analysis, the economic feasibility of using the DG's and storage devices has also been studied.

1.2 Conventional vs. Distributed generation

Conventionally, electric power is generated using generators at a central power station and is transmitted and distributed to the remote loads. The major concerns with these generation technologies are the limited supply and increased emission of CO_2 and other gases causing environmental pollution.

In recent years distributed or dispersed generation has been gaining popularity. There are a number of definitions that have been used for distributed generation. Generally, distribution generation is the process of connecting generators of relatively smaller capacities, as compared to central power station, close to loads. Primary sources to DG’s can be both non-renewable as well as locally available renewable energy such as wind, hydro, solar and biomass for generating electricity. DG’s are seen as a potential solution to the increasing load demand. Unlike the traditional generators these distributed generators have lower capacities, which range between several kW and a few MW. But there are cases where DG technologies are used to produce several MW of power [1]. The DG technologies have a number of technical as well as economic advantages as listed below:

- ☐ Acts as backup system during outages and interruptions of the main source to supply critical loads such as hospitals.
- ☐ Waste heat generated during the electricity production process can be utilized effectively for heating purpose. This process is called co-generation or combined heat and power.
- ☐ Using locally available renewable sources and wastes for the production of electricity decreases the dependency on oil and other non-renewable sources.

- DG technologies using renewable resources produce clean power with reduced emission of greenhouse gases.
- It is cost effective to use them as main sources in remote locations as they help in deferring some of the costs included in expansion and maintenance of the grid.

Though there are numerous advantages as mentioned above, a DG can have a positive effect only when the correct size and type is used. The major issues while interconnecting the DG’s to the grid are discussed in section 1.4 of this chapter.

1.3 Energy storage devices

Certain DG techniques such as wind and solar, do not output constant power at all times. The output of the wind turbine is dependent on the speed of the wind. Similarly the photovoltaic cells can supply power only as long as there is sunlight. In such cases, storage of power for later use becomes essential. The energy storage devices store power from the DG’s during times of normal output and low loads. This stored energy can be used at time when there is no DG output or during periods of high demands. There are many types of energy storage devices that are currently being used. These devices are explained in chapter 2. The storage device that needs to be used depends upon the application, amount of storage needed and the duration of storage. Since most of the storage devices are DC, we need power electronic interfaces to connect them to the AC system. Similar to the DG’s the storage devices also impact the performance of the system.

1.4 Major interconnection issues

DG’s can operate in two modes namely stand-alone and grid connected. The grid-connected mode has drawn a lot of attention and analysis recently, due to its impacts on the grid. Though the DG has a lot of advantages, it also has some negative impacts especially when connected to the grid. Certain issues that arise due to the interconnection are listed below [2]:

1.4.1 Technical issues

- Stability – Interconnection of the DG’s to the grid impacts the rotor angle, voltage and frequency stability of the grid. Based on the type and size of the generators the DG either improves or worsens the stability of the system.
- Power quality – The power quality of the grid has recently become a problem with the increased use of power electronic devices. A number of distributed generators are interfaced to the grid through power electronic circuits. Using these DG’s increases the already existing power quality problem.
- Voltage fluctuations – Power injected by certain DG technologies, such as wind turbines and photovoltaics, is fluctuating. This results in the local fluctuation of voltage.
- There is a certain limit on the number of DG units that can be connected to the system. This limit depends upon the size and type of the system. The reactive power that is supplied must be equal to the reactive power demand in order to maintain the voltage level of the system. Connecting more number of DG’s may

increase the reactive power supplied, thereby increasing the voltage level of the system considerably.

- DG’s increase the short circuit current during fault creating more challenging protection requirements. Therefore to use DG’s, improved protection devices need to be used which adds to the cost of the system.
- With more number of distributed generators it is difficult and takes a long time to locate any fault in the system. Also the direction of flow of current also becomes unpredictable.
- Existing radial distribution system and control are designed to handle power flow in just one direction. When DG’s are connected, power flows in both the directions. Therefore the existing systems need to be upgraded.

1.4.2 Economic issues

- Due to the unpredictable nature of the cost of fuels, it is difficult to properly plan the interconnection of DG’s to the grid. This results in financial problems to the customers.
- The network operator has to differentiate between power from the grid and the power from the distributed generators. This, results in issues related to the charge imposed on the power usage.
- As mentioned earlier, enhancement of already existing protection devices is necessary which adds to the cost of the system.
- Improvements needed in the system increase the total cost of the system.

1.5 Research work contributions

From the issues presented in the previous sections, the most critical technical issue is the stability of the system. There have been a number of studies on the both the steady state and the transient stability impacts of DG on systems. As mentioned earlier, energy storage devices also have significant impact on the system. But there is not much work done to analyze the impacts of both the DG's as well as energy storage devices on the grid. This work has contributed towards the transient stability analysis involving both, the DG's and energy storage devices. Based on the indicators and approach selected in the references, a procedure to analyze the stability has been obtained. This work also involves modeling of two energy storage devices, battery and ultracapacitor. These models have been developed using a first order equivalent circuit and are therefore simple yet appropriate representation of the actual battery and ultracapacitor. They can be easily scalable to any voltage and power levels with very minimal modifications.

1.6 Objectives of the thesis

This thesis aims at analyzing both the technical as well as economic impacts of using distributed generators as well as energy storage devices in the grid. As a first step in the analysis, an appropriate test system has to be developed. The first part of the study involves the transient stability analysis of the system. The main tasks in this part are:

- To analyze the stability of the system without energy storage devices. This includes analyzing the response of the different transient stability indicators to different types of faults and different penetration levels of the DG.

- Since there are no ready to use models of storage devices, it is necessary to develop models of battery and ultracapacitor in Simulink.
- The developed models are then connected to the test system by means of suitable power electronic interface after which the transient stability is analyzed as before

The second phase of the study is the economic analysis of the system with energy storage devices. The cost of the system is calculated, using HOMER, first without any storage devices and then with the two storage devices separately.

Finally the cost versus benefits of using the storage devices in a distributed network has been analyzed.

1.7 Thesis organization

Chapter 2 gives the background of different distributed generator technologies and energy storage devices. Previous studies related to transient stability analysis and economic analysis of the DG's is presented. A brief description of the different software packages used in the study is also given.

Chapter 3 focuses on the modeling of a battery. It includes the equivalent circuit and the necessary equations that are used for developing the model and presents the developed model of battery in Simulink.

Chapter 4 includes the equivalent circuit, necessary equations and the developed model of ultracapacitor in Simulink.

Chapter 5 presents the test system that has been used for the study. The features and details of the different components in the system are explained. The power electronic converter that is used in the study is also introduced. The transient stability analysis approach that has been used in this study is explained which includes the different indicators that are chosen, different test scenarios and the test procedure.

In Chapter 6, the results of transient stability analysis with DG's and without energy storage devices are discussed. The response of the transient stability indicators for different load and generation conditions are presented in this chapter.

Chapter 7 presents the results of the transient stability analysis with the energy storage devices. The results of different simulation scenarios with battery and ultracapacitors are given. After the analysis of all the transient stability indicators, the results are compared with and without the storage devices.

Chapter 8 deals with the economic aspect of the study. The cost analysis of the system with the battery and ultracapacitors has been done using HOMER. The procedure, simulation and results of the analysis are presented in this chapter.

Finally, Chapter 9 discusses the cost versus benefits of using energy storage devices in the grid and also presents the future work.

1.8 Summary

With the increase in use of distributed generators recently, the need for analyzing the stability issues related to its interconnection to the grid also becomes critical. The concept of distributed generation and energy storage was explained and the major issues of interconnection were also explained in this chapter. The objectives of the research work have been discussed and the organization of the thesis was presented.

1.9 References

[1] K.W Mitchell, R.R King and T.L Jester, “Cz Si photovoltaics: towards 100MW”, *Proceedings of the 25th IEEE Photovoltaics specialists conference, May 1996, pp 541-543.*

[2] www.leonardo-energy.org

CHAPTER II

BACKGROUND

2.1 Introduction

This chapter gives an introduction to the concept of distributed generation. Since it is necessary to understand the different types of DG technologies and storage devices, a brief overview of each of the type is given. Some of the previous work that has been done related to the transient stability of DG's and energy storage devices and economic feasibility are discussed. A brief description of the different software tools used is also given.

2.2 Conventional vs. renewable energy systems

Electric power is generally generated using conventional generators based on non-renewable energy sources such as coal, oil, natural gas and nuclear. The capacity of these generators is very high, as they are required to produce bulk amounts of power necessary to supply the entire loads. Supply of fuels for these generation technologies is limited and creates the need for looking at alternative renewable fuel sources.

Figure 2.1 shows the distribution of different sources of energy that are currently used in the US as reported by the Department of Energy [2]. The pie sections are based on the number of generators that are used. It can be seen from the figure that the percentage of renewable energy used for the generation of electricity is very small. This small percentage includes electricity from solar, biomass, geothermal, hydroelectric and wind resources.

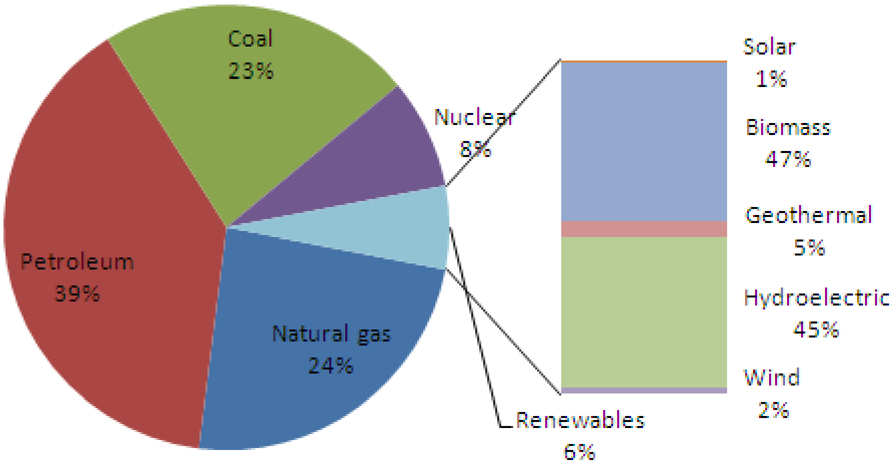


Figure 2.1 Distribution of energy sources for the year 2006 as reported by the DOE [2].

It can be seen that the percentage of generators that use renewable sources of energy is only about 6% of the total. According to the Distributed Power Coalition of America (DPCA), by 2010 about 20% of the power in the United States is expected to be generated from renewable sources [3]. Some of the most commonly used DG technologies are explained in Section 2.3.

2.3 Distributed generation technologies

There are numerous DG technologies that are gaining popularity recently. A few of the most commonly used ones are the Internal Combustion engines, microturbines, wind, solar panels, fuel cells and biomass and a brief description of each is given below.

2.3.1 Internal combustion engines

The internal combustion engines are traditionally used as backup generators that are powered by diesel. They are connected to the grid by means of synchronous generators. The typical capacities range between 50 kW and 5 MW. The advantages and disadvantages of this technology are listed below [3].

Advantages:

- Has the lowest capital cost compared to all the other DG technologies
- Can be used to produce both electrical and thermal energy (Co-generation)
- Has good efficiency of about 35%

Disadvantages:

- Emission of greenhouse gases is more than most of the other renewable technologies
- Though the capital cost is low, the maintenance cost is very high compared to other technologies
- Due to large number of moving parts in the engine, there is a lot of noise produced during its operation

In spite of all these disadvantages, this is the most commonly used DG technology until now.

2.3.2 Microturbines

These are small combustion engines whose capacity ranges between 25 kW and 150 kW. It consists of a compressor and a turbine mounted on the same shaft as that of the generator. The generator is usually synchronous and the efficiency of the microturbines is between 25% and 30%. Since they have smaller number of moving parts compared to the ICE, the maintenance cost and the noise during operation are reduced. The emission level is less than that of the ICE but is still significantly higher than other technologies using renewable sources. In addition to the emission problems, the major concerns related to the microturbines are their very high capital costs and shorter operating lifetime [4].

2.3.3 Wind turbines

The wind turbines use either induction generators or inverters to supply power to the grid. The typical capacity of wind turbines can lie anywhere between a several hundreds of watts to a few MW. One major issue that had been limiting the use of wind turbines for a long time is that, these turbines operate at variable speed and therefore need suitable inverters to be connected to the grid. Though the recent advancement in power electronics provides a solution to this technical issue, the cost of the inverters still limit their large-scale usability. The inconsistency in the output power generated makes it essential for suitable storage devices to be used along with the wind turbines.

Figure 2.2 shows a doubly fed induction generator, which is used in most of the wind turbines today [5]. Here the stator winding is directly connected to the grid and the rotor winding is connected through a converter.

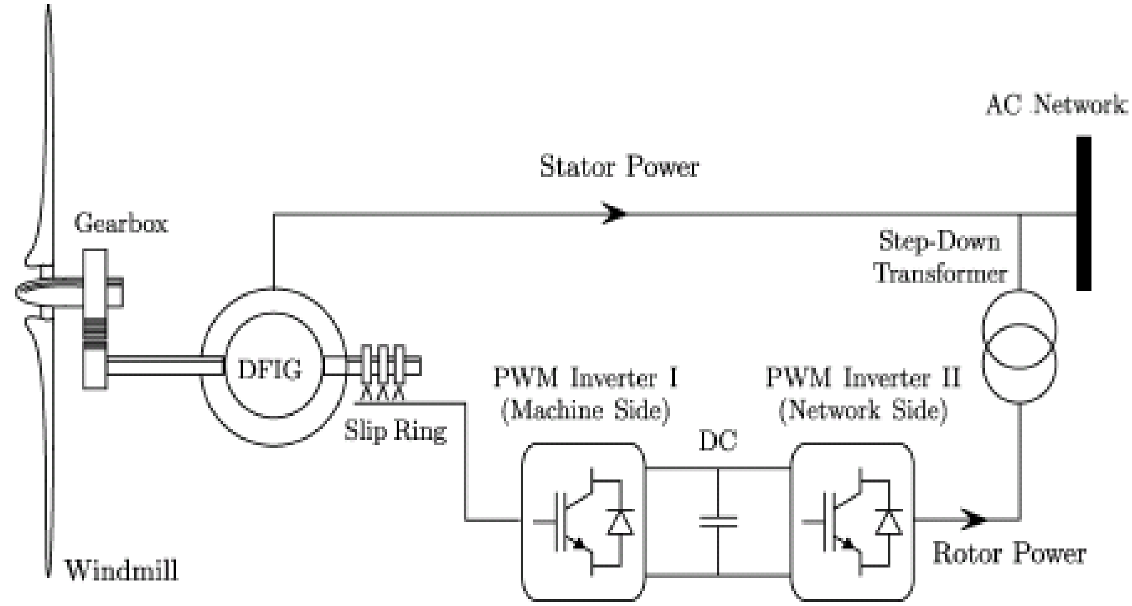


Figure 2.2 Doubly fed induction generator used by the wind turbines [27]

2.3.4 *Photovoltaics*

Photovoltaics or solar panels are developed technologies that use the abundant energy from the sun to produce electricity. Solar cells are made up of semiconductors which when hit by the photons from the sun's rays, get illuminated, thereby generating electricity [6]. They are capable of generating power as long as the sun shines after which it stops. In realtime applications a number of cells are interconnected together to form a PV module. The number of cells that are connected depends upon the required capacity. The DC power that is produced is converted into AC by means of inverters before connecting the panel to the grid. The current challenge in large-scale installation of PV is their very high installation costs.

2.3.5 *Fuel cells*

Fuel cells are a promising technology that is used in a wide range of applications such as vehicles, co-generation and DG power applications. Fuel input to the cells can be either non-renewable such as natural gas or renewable such as biogas. Based on the type of electrolytes there are a number of classifications of fuel cells out of which the proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC) are most commonly used in distributed power applications. The current cost of fuel cells is in the range of $ 5000 to $ 5600 per kW [7]. It is predicted that with further enhancement and advancement in the cell technology, the cost can be reduced up to $1000 per kW in the near future thereby increasing its competitiveness with other conventional generators.

2.3.6 Biomass generators

Biomass resources are converted into biofuels such as ethanol and biodiesel by means of two types of conversion processes namely biochemical and thermochemical conversion. In the U.S, the commonly used biomass resources are soybeans, switchgrass, residue from industries, feedstock and municipal waste. The intermediate product in the biochemical conversion of biomass to ethanol is synthetic gas or syngas which can be used as input to the generators along with other fuels [8]. Similar to other renewable energy generators, this also reduces the amount of greenhouse gases. Due to the variation in the cost of fuels such as diesel and gasoline, it is generally difficult to compare the cost of the biofuels with the traditional fuels. During periods when the diesel prices are high the biomass generators can be more economical than the traditional generators whereas when the traditional fuels are cheap the biomass generators can be comparatively costly.

But it has to be mentioned that biomass generators have numerous other benefits that are not reflected by the cost of biofuels. At present biofuels are more commonly used in transportation applications, but there is an increasing use in distributed power applications also.

2.4 Energy storage technologies

As mentioned in the previous section, the output of certain renewable energy resources such as wind and solar is unpredictable. In such cases energy storage devices can be used to augment the DG's when it fails to fulfill the load requirements. In addition to supporting, the storage devices have also been identified to decrease the negative impacts of the DG's on the grid [10, 11 and 12]. There are varieties of energy storage devices each of which have different techniques for storing energy. Based on its features and characteristics, the best devices are chosen to be used in the distributed applications. This section provides an overview of the features of some of the devices that are used in distribution applications.

2.4.1 Batteries

These are the most commonly used type of storage devices in distributed applications. A lot of research done earlier has proved that batteries are both technically as well as economically advantageous [13, 14]. Recently there has been a lot of advancement in the type of material used in the batteries, which make them more feasible to be used in a wide range. Of all the types, lead acid batteries are the most commonly used ones even today. But it has to be mentioned that Li-ion batteries are gaining a lot of popularity mainly due to their high energy densities, energy capabilities and lifetime compared to the lead acid batteries. Though their maintenance costs are low compared to the lead acid batteries, their capital cost is very high, which is the reason for their limited use. In this study we focus on the Li-ion batteries, the modeling of which is explained in detail in chapter 2 of this thesis.

2.4.2 Ultracapacitors

Ultracapacitors are also electrochemical devices that have started to establish themselves as power sources capable of quickly recharging and supplying power. They have slowly started to replace the traditional batteries in hybrid vehicles. In distributed applications, they have been used together with the batteries to act as storage devices but so far have not been used independently. Similar to Li-ion, the capital cost of the ultracapacitors is very high, which is the major concern in their large-scale use. It has been suggested that if their capital cost is cut down, they would readily replace batteries and find a new market for themselves [15]. The ultracapacitors have very high power densities compared to the batteries, with almost unlimited number of charging and discharging cycles. Modeling of the ultracapacitor is explained in chapter 3 of this thesis.

2.4.3 Flywheels

This is a very old and simple form of energy storage. In the flywheels energy is stored in the mechanical form. The flywheel is coupled to a motor/generator set and the energy stored depends upon the speed at which the rotor rotates. When current flows into the motor, the rotor starts to rotate fast which causes the flywheel to charge [16]. During the discharge, the current flows out which decreases the speed of the rotor. The amount of energy stored is proportional to the moment of inertia of the flywheel (J) and square of the rotational speed (ω). This is represented by the equation: $E_{FW} = {}^{1}/_{2}\, J * \omega^2$

They have a very quick response and are therefore used in applications that require quick supply of stored energy. Based on their speed with which they rotate, the flywheels can be classified as either high speed or low speed. Since the energy stored is dependent on the speed of rotation high speed flywheels store more energy than the low speed ones. They can also be either together with the batteries or also as a replacement to the batteries.

2.4.4 Superconducting Magnetic Energy Storage (SMES)

The SMES, which consists of superconducting coils, supplies electrical energy directly with no conversion of energy into chemical or mechanical forms. When current flows into the coil a magnetic field is created around the coils in which energy is stored. These coils are capable of discharging large quantities of power within a short period. They are ideally suited for supplying high power for short periods. For instance certain SMES devices supply about 1 to 2.5 MW for nearly about 15 minutes.

Figure 2.3 shows the power and energy capacities of different energy storage devices. Each of the devices has its own advantages and disadvantages.

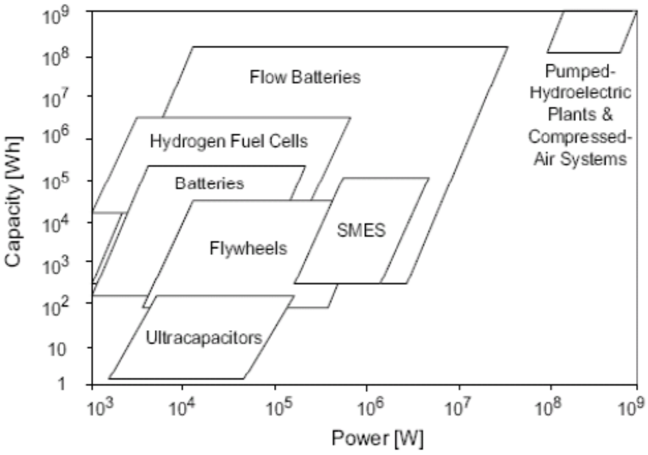


Figure 2.3 Power and energy densities of different energy storage devices [23].

2.5 Technical and economic impacts of DG’s

2.5.1 Transient stability impacts of DG

As mentioned in the previous section interconnection of DG to the grid impacts the stability of the grid to a great extend. In the earlier DG studies, the impacts on transient stability were almost neglected since the most important objective at that point was to produce electricity from renewable energy. When the size of DG is quite small, its impacts on the transient stability will be negligible and therefore can be neglected. But with the increase in the number of DG’s it becomes essential to analyze the transient stability. It is only in the recent years that greater focus is given on the stability impacts due to increasing usage of DG’s and their bigger sizes.

In reference [18], the transient stability of the New England test system is analyzed. The analysis includes asynchronous generators, controlled and uncontrolled synchronous generators as well as controlled and uncontrolled power electronic converters. In this approach a fault is applied to the system for 150 ms and the response of the different generator technologies with different penetration levels are monitored. The response of these generator techniques are analyzed by means of three indicators namely rotor speed deviation, oscillation duration and the terminal voltage. This study proved that increase in the number of DG's improved the stability of the system irrespective of the type of technology used.

Similar approach has been used in reference [19], to analyze the angle, frequency and voltage stability of a 245-bus system. In this study, the power angle between two generators, the deviation in frequency and voltage deviation is analyzed when a fault of 100ms is applied to the system. Similar to the previous work, in this also it was seen that with more DG percentage, the stability of the system improves.

2.5.2 Economic impacts of DG

In the work done by Zoulias and Lymberopoulos [21], the technical as well as economic feasibility of replacing the traditional technologies by the recent distributed technologies such as PV and fuel cells is analyzed using HOMER. A PV-diesel based power system is first simulated to obtain its economics. Then the diesel generator is replaced by a hydrogen-based fuel cell and the simulation is carried out to find the economics of the new system. Finally, both the systems are compared and it was found out that, though replacing the conventional sources is technically favorable, the system can be economically favorable only when the cost of the electrolyzer and hydrogen tanks are reduced by around 40-50%.

Khan and Iqbal [22] have done a pre-feasibility study on a hydrogen based hybrid system. This consisted of DG technologies such as fuel cell, photovoltaic, wind generators and battery as the storage device. The system was based on the applications in Newfoundland. The results of the study suggested that using the emerging hydrogen based system was not cost effective when compared to the conventional one. It also suggests that there needs to be more advancement in the technologies before it is being called a feasible system.

Similar other studies have also suggested that though under present conditions the DG's and advanced storage devices cannot be declared cost effective, it is sure that with more advancement in technologies and reduction in costs, they will replace the conventional generators and storage devices in future.

The approach in this study is based on the references mentioned above but with certain modifications. The technical part of the study will include the analysis of transient stability by means of indicators selected based on references. Analysis of the system is done with and without energy storage devices and for different penetration levels of the DG. The economic aspect of the research aims in analyzing the cost of the system with and without energy storage devices.

2.6 Simulation tools used in the study

Two simulation softwares have been used in the research. A brief description of the software packages is given in this section.

2.6.1 MATLAB/ Simulink

For the technical analysis, MATLAB/ Simulink version 7.4 [24] has been used. Simulink has been selected due to the reason that it is user-friendly and consists of a number of ready to use models. The power system components in the Simulink library include different types of generators, loads, transformers, faults and other components, which can be used to build and analyze the necessary test system. There are no built-in energy storage models in Simulink. Though there are no built-in models of energy storage, it can easily be built using the basic blocks that are present. The response of the selected indicators are monitored and recorded by means of the scope.

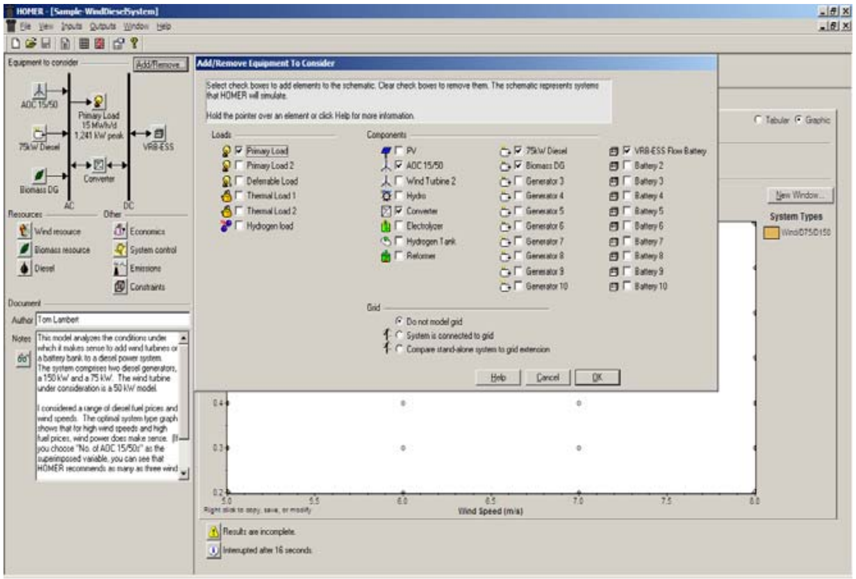
2.6.2 HOMER

Hybrid optimization for electric renewables (HOMER) is an optimization software that has been developed by the National Renewable Energy Laboratory (NREL) for evaluating both grid connected as well as off grid hybrid systems [25]. It suggests a list of cost effective systems under the conditions specified by the user. It has a very user friendly GUI, by means of which, the necessary components are added or removed from the system. The major components in HOMER include power sources (including fuel cells, photovoltaics, biomass generators, and hydro and wind turbines) loads and batteries. Once the components are selected and assembled, the size cost and other data of each can be set through the component windows. The left part of figure 2.4 shows a system built in HOMER and the toolbar on the right is where the components are added or removed.

After the simulation is run, two types of results are presented, namely the sensitivity analysis and optimization. Sensitivity analysis is used to determine the effect of sensitive variables (such as wind speed, diesel price etc.) on the total cost of the system. The optimization result suggests a list of various sizes and combination of the components in order of their cost. Apart from the technical and cost issues, HOMER also deals with certain environmental constraints such as amount of CO and CO_2 emission by the system.

In summary, HOMER can be used for three different purposes, which are:

- To analyze the cost of a hybrid system before installation.
- To find out the cost effective sizes and combinations of the necessary components in the system.
- To analyze the cost of an already built or existing system.



Author: Tom Lambert

Notes: This model analyzes the conditions under which it makes sense to add wind turbines or a battery bank to a diesel power system. The system comprises two diesel generators, a 150 kW and a 75 kW. The wind turbine under consideration is a 50 kW model.

I considered a range of diesel fuel prices and wind speeds. The optimal system type graph shows that for high wind speeds and high fuel prices, wind power does make sense. (If you choose "No. of ADC 15/50s" as the superimposed variable, you can see that HOMER recommends as many as three wind

Select check boxes to add elements to the schematic. Clear check boxes to remove them. The schematic represents systems that HOMER will simulate.

Hold the pointer over an element or click Help for more information.

Loads:
☑ Primary Load
☐ Primary Load 2
☐ Deferrable Load
☐ Thermal Load 1
☐ Thermal Load 2
☐ Hydrogen load

Components:
☐ PV
☑ ADC 15/50
☐ Wind Turbine 2
☐ Hydro
☑ Converter
☐ Electrolyzer
☐ Hydrogen Tank
☐ Reformer
☑ 75kW Diesel
☑ Biomass DG
☐ Generator 3
☐ Generator 4
☐ Generator 5
☐ Generator 6
☐ Generator 7
☐ Generator 8
☐ Generator 9
☐ Generator 10
☑ VRB-ESS Flow Battery
☐ Battery 2
☐ Battery 3
☐ Battery 4
☐ Battery 5
☐ Battery 6
☐ Battery 7
☐ Battery 8
☐ Battery 9
☐ Battery 10

Grid:
● Do not model grid
○ System is connected to grid
○ Compare stand-alone system to grid extension

Results are incomplete.

Interrupted after 16 seconds.

Figure 2.4 Graphical user interface in HOMER

2.7 Summary

Various DG techniques and storage devices that are currently used have been explained in the initial part of the chapter. The next part discusses the different approaches that have been followed by earlier researchers to analyze the transient stability and also for the economic analysis. Finally, the software tools that have been used in this research are also discussed.

2.8 References

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CHAPTER III

ELECTRICAL MODELING OF BATTERY

3.1 Introduction

Batteries are one of the most efficient and economic devices for storing energy. There are wide varieties of batteries that can be used for energy applications. The most general requirements of a good battery are as given below [1].

1. It has to supply adequate power to meet the load demand, when needed.
2. It has to last for a considerably long period of time and should be economical.

Generally, batteries can be defined as sources of energy that supplies the required power by converting chemical energy into electrical energy. Battery is a term that is commonly used to indicate a group of electrochemical cells that are interconnected in series or parallel. Figure 3.1 explains the working principle of each cell.

The anode and the cathode are separated by the electrolyte, which is either a solid or liquid. The two electrodes are connected through an external device. During the process of energy conversion, oxidation takes place at the anode and reduction takes place at the cathode. During the discharging process the electrons is passed from the anode to the cathode and the electrons are made to flow from the cathode to the anode during the process of charging. The difference in the potential energy is measured in terms of volts and is known as the terminal voltage of the battery or the battery voltage. The voltage of an individual cell is generally less and therefore a number of cells are connected in series to obtain a higher voltage level.

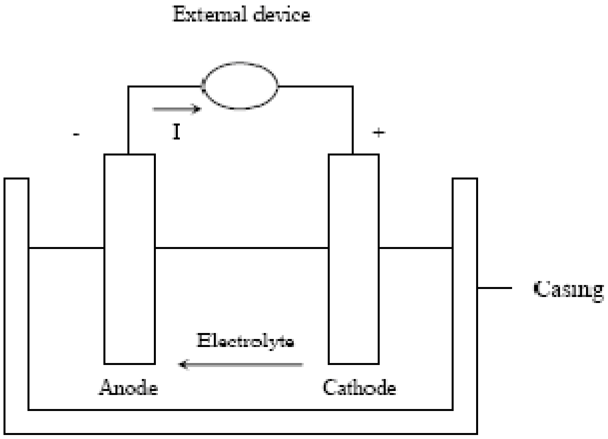

Figure 3.1 Principle of operation of an electrochemical cell

3.2 Classification of cells

Batteries can be classified based on the following criterion.

1. Recharge and use
2. Material used for electrodes and electrolytes
3. Power level

If a battery is used only once and cannot be charged in order to use again, then it is called a *primary battery*. On the other hand, if the battery can be recharged and used for a number of times, it is called a *secondary battery*.

Some of the common types of cells are explained below:

1. Lead Acid:

This is one of the most commonly used battery type. In the lead acid batteries the electrodes are made of lead metal (Pb) and lead oxide (PbO_2) and the electrolyte is a solution of sulfuric acid. As the battery is discharged, the electrolyte solution keeps decreasing causing a decrease in the lifetime of the battery. This is one of the major disadvantages of a lead acid battery. Another concern in using these batteries is the high maintenance cost due to the explosive nature of the acidic electrolyte solution. The nominal voltage of each lead acid cell is about 2.1 to 2.2V and its charge/discharge efficiency is about 75 – 92%.

2. Nickel Cadmium (NiCd):

With nickel hydroxide as the anode, cadmium as the cathode and potassium hydroxide as the electrolyte, the working of the NiCd cells are similar to the lead acid cells. The biggest advantage of using NiCd is that the charge/discharge rate is very high. It has higher energy density than the lead acid batteries. In spite of these advantages NiCd cells are not commonly used as lead acid because of the dangerous toxicity of the cadmium. The cost of these cells is also higher. The nominal voltage of these cells is around 1.2 V.

3. Nickel - Metal Hydride (NiMH):

This is similar to the NiCd cells except for the fact that the anode is a metal formed from different compounds, instead of cadmium. Since the capacity of these cells is three times more than the NiCd cells, these are considered to replace the NiCd cells. The nominal cell voltage is about 1.2 V.

4. Lithium-Ion (Li-ion):

The anode and cathode of the Li-Ion cell is made up of materials that allow lithium to migrate in and out of it. In most of the commercially available cells the anode is made of carbon and cathode is a metal oxide [7]. The electrolyte is a lithium salt in an organic solvent. Unlike lead acid cells, the maintenance cost of the Li-Ion cells is much lower. These cells also have a higher nominal voltage that ranges between 3.6 and 4.2 V. Due to higher voltage levels of the individual cells, the weight of the batteries (formed by grouping the individual cells) is low compared to the other types. The major concern when using these cells is the temperature. It should not be used at extremely low temperatures. Temperature constraints on the Li-Ion cell are discussed later in this Chapter.

5. Lithium-Ion polymer:

These are an advancement to the older Lithium-Ion cells. The main difference between the lithium-ion and the lithium-ion polymer cells lie in the casing that presses the cathode and the separator. In the former this casing is a rigid metal whereas in the latter type it is made of polymer cells. Compared to other types of cells, these have approximately 20% more energy density. The nominal voltage of these cells is 3.7 V, which is higher than most of the other cells. In spite of these advantages, it is not used widely as other types of cells because of its very high cost. Another major drawback with these cells is its longer charging time, which is approximately 1 hour, for a full charge. A comparison between different types of cells is presented in Table 3.1.

Table 3.1 Overview of the different types of secondary cells

Battery type	*Nominal voltage (Volts)*	*Energy density (Wh/ kg)*	*Life cycle (cycles)*	*Energy efficiency (%)*	*Cost ($ per Wh)*
Lead acid	2.1 / 2.2	30 – 40	500 – 800	70 – 92	0.17
NiCd	1.2	40 – 60	2000	70 – 90	1.50
NiMH	1.2	30 - 80	500 – 1000	66	0.99
Li-ion	3.6 / 4.2	160	3000	99.9	4.27
Li-ion polymer	3.7	130 – 200	>1000	99.8	-

After analyzing the pros and cons of all the types of cells, Li-Ion is selected to be used in the study. The major reasons for selecting this type are listed below.

1. High voltage levels – the number of cells required to form a battery bank is reduced due to the higher voltage levels of the individual cells.
2. High energy density – size of the battery banks will be lesser for a specific energy requirement compared to other types.

3. Long life cycle – 3000 cycles.
4. Very high efficiency – near 100%

3.3 Lithium-Ion cell

3.3.1 Cell chemistry:

As mentioned earlier, the Lithium-Ion cell consists of a carbon anode, a metallic cathode and an organic electrolyte. In most of the commercially available cells the anode is graphite and the cathode is made up of a material that is capable of allowing lithium to penetrate in and out of it. The reactions at the anode and the cathode can be described by the following equations:

At the anode: $Li_x C \leftrightarrow C + xLi^+ + xe$ (3-1)

At the cathode: $Li_{1-x}MO_2 + xLi^+ + xe \leftrightarrow LiMO_2$ (3-2)

where:

C is carbon (graphite) and M can be either CO or Ni or a mixture of both.

The electrolyte used in the Li-Ion cell is selected based on two criteria [7]:

1. It has to be stable and efficiently form a solid electrolyte interface (SEI) on the anode material (graphite)
2. The electrochemical potential of the electrolyte has to range from 0V to at least 4.3 V.

Some of the most commonly used electrolytes for Li-ion cells depend on $LiPF_6$ and a mixture of binary solvent. The major concern while selecting the electrolytes is their flammability. Certain additives are added to the electrolytic solution to make sure that the flammability is lowered

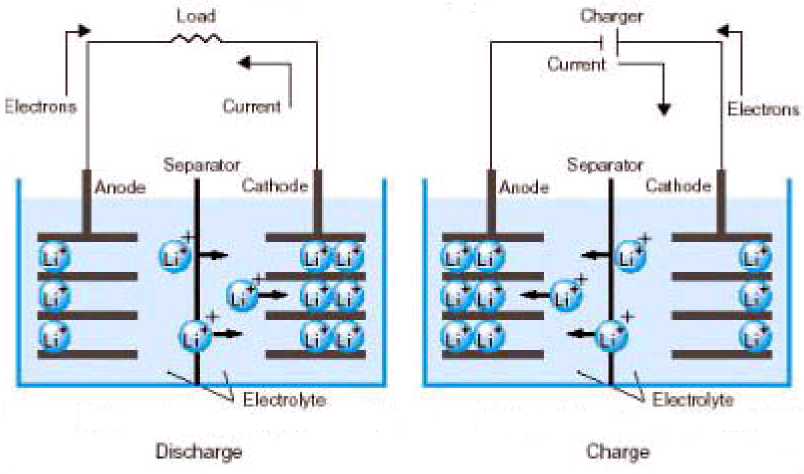

Figure 3.2 Charging and discharging processes in a Li-ion cell [4]

Charging and discharging processes in a Li-Ion cell is shown in Figure 3.2. During the discharging process (when the cell supplies energy) lithium is extracted from the anode and is passed into the cathode whereas during the charging process (when energy flows into the cell) lithium is extracted from the cathode and passed into the anode.

3.3.2 Cell construction:

Most of the cells that are commercially available today are either cylindrical or prismatic in shape. Figure 3.3 gives the construction of a cylindrical Li-Ion cell. The negative and positive electrodes are supported by Cu and Al foils respectively. Layers of separators can be found between these electrodes. The cathode itself acts as the casing for the construction. Insulators are a very important component in these cells. The gas release vents and gaskets add to the safety of the cell.

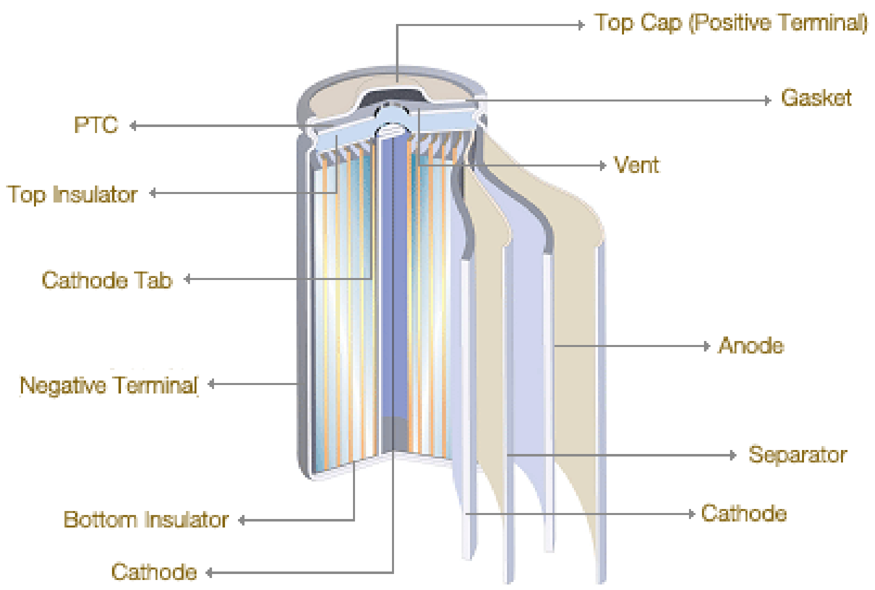

Figure 3.3 Construction of cylindrical Li-ion cell [5]

3.3.3 Cell performance:

The general parameters of the cell such as specific energy, energy density and cycle life depend on the type of cathode that is used [7].

Table 3.2 Performance of Li-ion battery (8 single cells) for Ni-Co and Mn cathodes

Parameter	*Ni-Co positive*	*Mn positive*
Battery Energy (kWh)	2.3	2.5
Specific energy (Wh/kg)	128	122
Energy density (Wh/L)	197	255
Energy efficiency (%)	98	96
Cycle life (cycles)	900	1200

The values of different parameters for two different cathode types are given in Table 3.2. It can be seen from the table that using Mn cathode results in better performance as compared to the Ni-Co cathode.

Temperature characteristics:

The performance of the Li-ion cell depends to a great extent on the temperature, at which it is operated. Figure 3.4 gives the performance curve of a standard 18650 Li-ion cell.

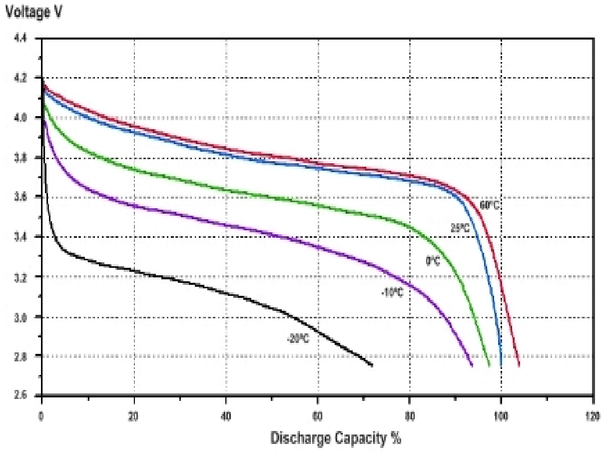

Figure 3.4 Performance curves of an 18650 cell at different temperatures [6]

It can be seen from the curves that performance of the cell decreases with the decrease in temperatures. At extremely low temperatures, the electrolyte in the cell freezes, thereby decreasing the operating voltage level of the cell. It can be seen that the drop in the operating voltage during discharge is very high for an operating temperature of -10°C as compared to 60°C. Similarly extreme high temperatures also affect the chemicals in the cell resulting in decreased operating voltage and increased self discharge. Therefore it is necessary to maintain the operating temperature between safe limits in order to improve the performance. The typical value in most cases is taken to be 25°C.

Self discharge rates:

Self-discharge of a cell is defined as the leakage in the current between the anode and the cathode, due to certain chemical reactions that take place within the cell. Even if the cell is not used, it can still get discharged to a certain level due to the internal reactions. The rate at which the cell gets self-discharged depends on the cell chemistry as well as on the temperature at which it is being operated.

Figure 3.5 shows the self-discharge rates of a standard cell at different temperatures.

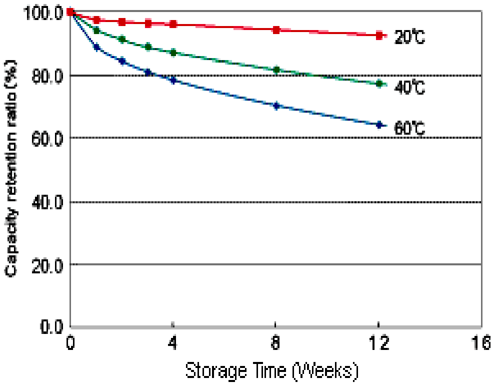

Figure 3.5 Self-discharge rates of an 18650 cell at different temperatures [7]

At high temperatures, the rate of self-discharge is greater when compared to lower temperatures. It should be noted that the self-discharge rate of a Li-Ion cell is very less as compared to other cells. In Li-Ion it is 2% to 3% per month whereas in NiCd it is

15% to 20% per month, in NiMH it is about 30% per month and in Lead acid it is 5% to 6% per month.

Discharge rate:

The rate of discharge of the cell also plays a vital role in its performance. Practical experiments have proven that the capacity of the cell decreases if the discharge time is more.

This can be seen from Figure 3.6, which clearly shows the capacity curves of the cell at different discharge rates.

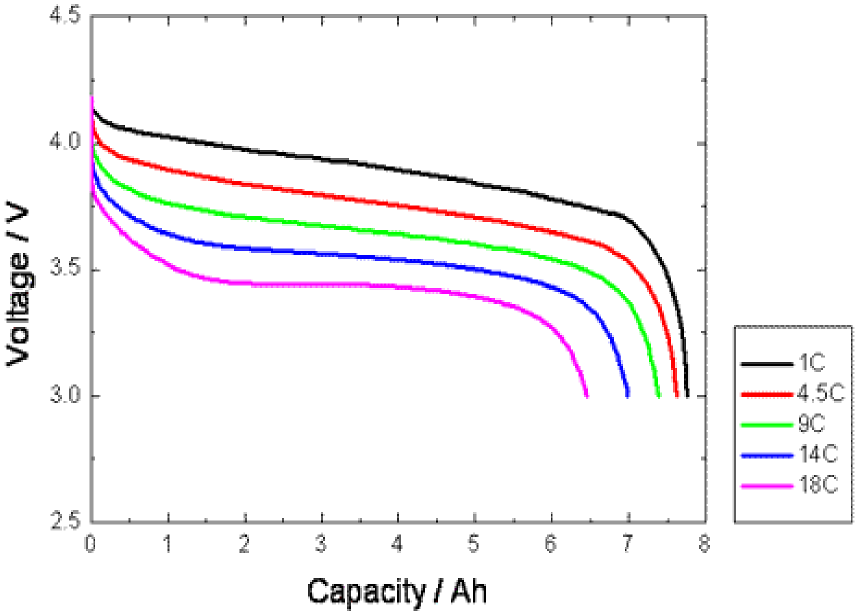

Figure 3.6 Discharge curves of an 18650 cell [7]

State of charge (SOC)
:

State of charge of a cell denotes the capacity that is currently available as a function of the rated capacity. The value of SOC varies between 0% and 100%. If the SOC is 100% then the cell is said to be fully charged whereas an SOC of 0% indicates that the cell is completely discharged. In practical applications, the SOC is not allowed to go beyond 50% and therefore the cell is recharged when the SOC reaches 50%. Similarly, as the cells start aging, the maximum SOC starts decreasing. This means that for an aged cell a 100% SOC would be equivalent to 75% to 80% SOC of a new cell.

3.4 Battery design considerations

The term battery denotes a group of individual cells connected in a series or parallel connection. Designing a battery bank depends on the following conditions:

- ☐ *Bank voltage* – The total voltage of the bank is met by connecting the cells in series.

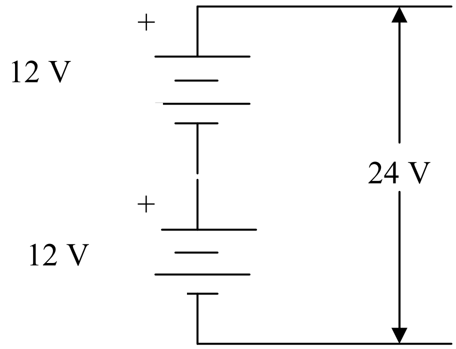

Figure 3.7 Series connection of cells

Figure 3.7 shows the series connection of cells to obtain higher voltage levels. It can be seen that a 24V battery bank is obtained by connecting two 12V cells in series.

☐ *Bank capacity* – Connecting the cells in parallel can increase the capacity of the battery bank. Parallel connection increases only the capacity whereas the voltage level of the bank remains the same as shown in Figure 3.8.

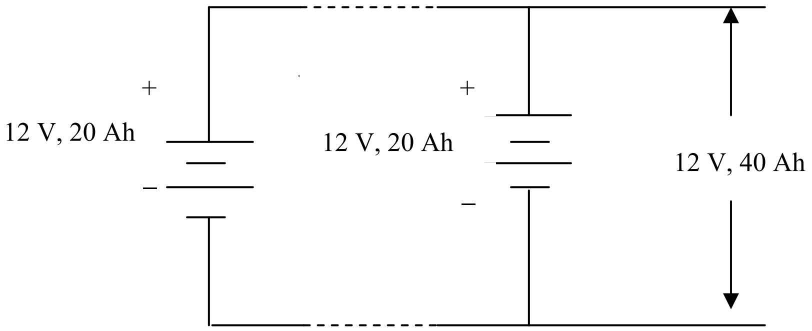

Figure 3.8 Parallel connection of cells

3.5 Equivalent circuit model of the battery

In order to use in simulations, an electrical model of the battery needs to be developed. In this study a linear model of the battery is used which is given in Figure 3.9.

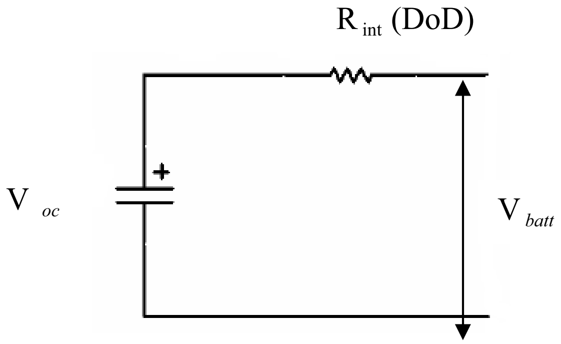

Figure 3.9 Equivalent circuit model of a battery

3.5.1 Battery parameters:

The main parameters that need to be considered while modeling the battery are:

1. Depth of discharge (DoD): It represents the total amount of energy that has been discharged by the battery. It is obtained by integrating the current flowing with respect to time.
2. State of charge (SOC): It represents the remaining capacity of the battery as a function of the maximum capacity. SOC is obtained by integrating the current flowing through the battery with respect to time and then subtracting it from the maximum capacity of a fully charged battery or simply by subtracting DoD from 1.
3. Internal resistance (R_{Int}): The graph given below shows the relationship between the internal resistance and depth of discharge [3].

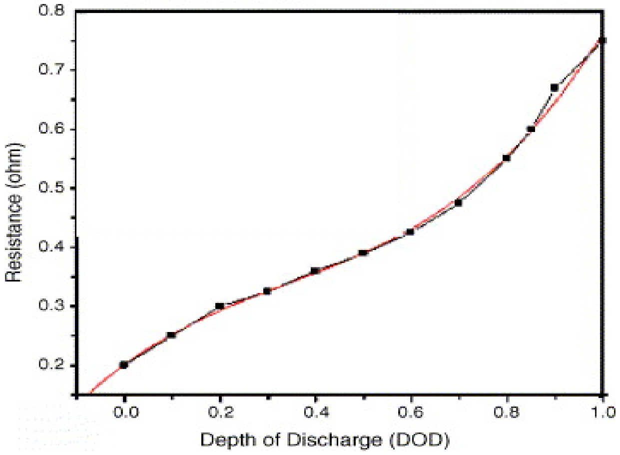

Figure 3.10 Battery internal resistances as a function of DoD [3]

Internal resistance is defined as the resistance to the current flow inside the battery as a result of various electrochemical factors (electrode surface area, conductivity of the electrolyte etc). The battery internal resistance is generally expressed as a function of the state of charge.

4. Open circuit voltage (V_{oc}): It represents the terminal voltage of the battery under no-load conditions (open circuit). It is also a function of the depth of discharge. The relationship between open-circuit voltage and the DoD is given in Figure 3.11 [3].

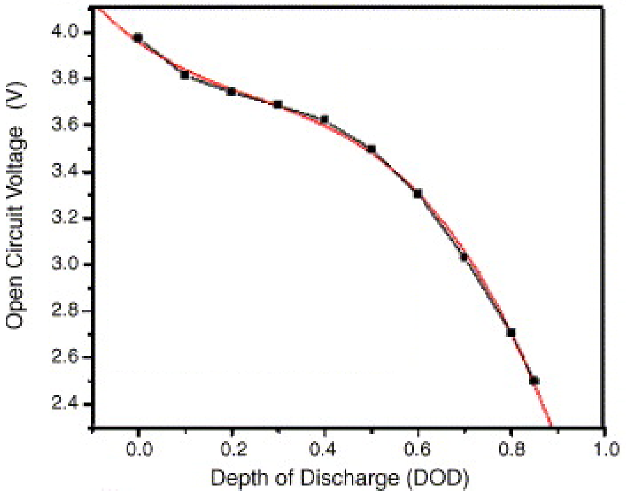

Fig 3.11 Open circuit voltage as a function of DoD [3]

3.5.2 Battery design equations:

The equations necessary for the modeling of the battery are given below.

$$V_{batt} = V_{oc}(DoD) + I_B * R_{int}(DoD) \quad (3\text{-}3)$$

$$DoD = \frac{1}{Q_{max}} \int I_B * t \; dt \quad (3\text{-}4)$$

$$SOC = \frac{Q_{max} - Q_{used}}{Q_{max}} = 1 - DoD \quad (3\text{-}5)$$

$$R_{int} = 0.20139 + 0.58863*DoD - 0.81697*(DoD)^2 + 0.79035*(DoD)^3 \quad (3\text{-}6)$$

$$V_{oc} = 3.95587 - 1.42918*DoD + 2.83095*(DoD)^2 - 3.7497*(DoD)^3 \quad (3\text{-}7)$$

where:

V_{batt} = Terminal voltage of the battery (V),

I_B = Curent flowing through the battery (A),

Q_{max} = Maximum battery capacity at fully charged/discharged conditions (Ah),

Q_{used} = Used battery capacity (Ah).

The expressions for Rint and Voc are obtained from reference

It must be mentioned that the charging/ discharging of the battery is based on the direction of flow of current. If the current, I_B, is positive then the cell is considered to be discharging and on the other hand if it is negative, the cell is considered to be charging. The empirical formula governing the relationship between R_{int} and DoD, V_{oc} and DoD are obtained from experiments conducted on a Sony 18650 cell and is taken from [3].

3.6 Model of the battery in Simulink

Using the circuit and equations mentioned in the previous section, a model of the battery is built in Matlab/ Simulink as seen in figure 3.12. The inputs to the model are the required power and the initial SOC of the battery. The data that has been used in the modeling is obtained from the individual data sheet of the Sony 18650 Li-ion batteries. The value of internal resistance, R_{int} as given in the data sheet is taken to be 0.015Ω.

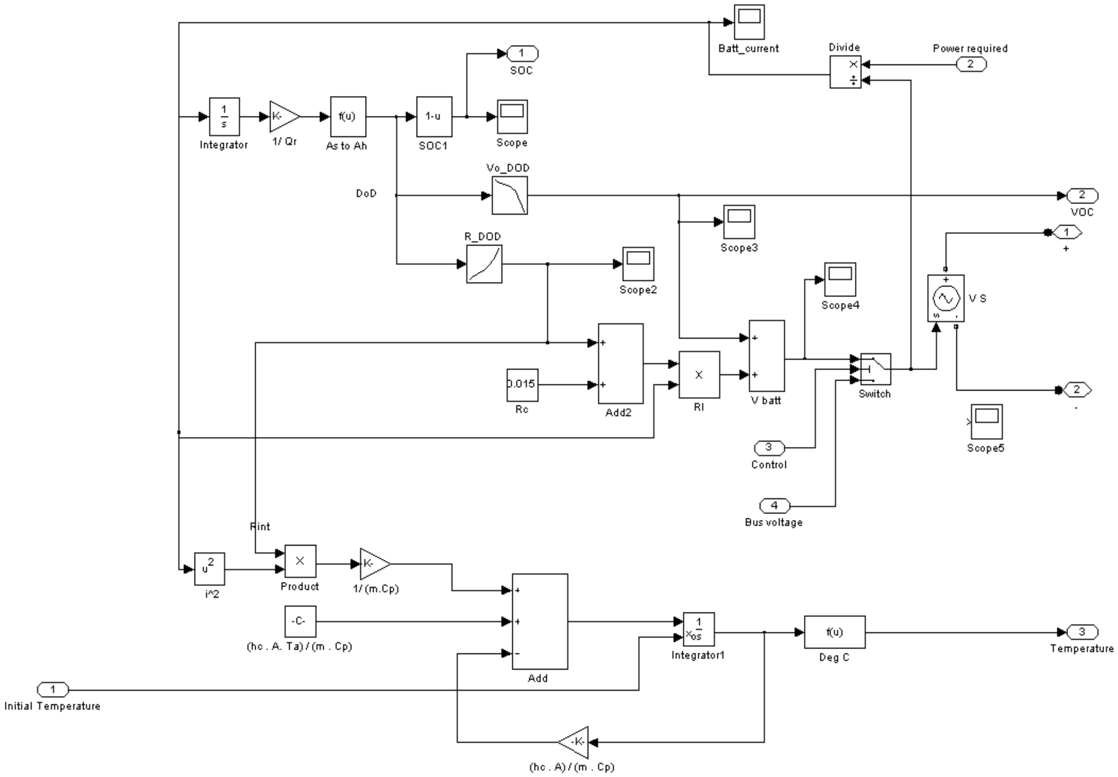

Figure 3.12 Simulink model of the Li-ion battery

Similar to the battery modeling, a model of the ultracapacitor is also built in Simulink. The following chapter deals with the modeling of the ultracapacitor.

3.7 Summary

Different types of cells have been discussed in this chapter. Based on the characteristics, the Li-Ion was selected to be used in the study. The characteristics, equivalent circuit and the design equations of the battery were discussed. Finally the model of the battery that was built in Simulink was presented.

3.8 References

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CHAPTER IV

ELECTRICAL MODELING OF ULTRACAPACITOR

4.1 Introduction

Ultracapacitors, also called supercapacitors or electrical double layer capacitors, are electrochemical storage devices that are gaining popularity in recent days because of their large power and energy densities. It is different from the ordinary capacitors by the type of electrodes that is used. The carbon technology that is used in them creates a bigger surface area for a smaller separation of the electrodes. Though it stores much lesser energy as compared to the batteries, it has almost unlimited life period. Unlike batteries, the ultracapacitors are not commercially available in large scale for DG applications, but will definitely be used in the near future due to its tremendous advantage compared to the battery. The most important drawback of the ultracapacitors that prevents its usage in large scale is its high cost. A number of ultracapacitor manufacturers are working on reducing the cost, making sure that it would be available at lower initial costs in the market similar to batteries. Similarly a lot of advancements are being done to develop the technology to improve the energy density of the cells making them suitable for use in long-term applications.

As it is predictable, that ultracapacitors would be used in the near future for storing energy from the distributed systems and therefore it has also been included in this research. This chapter deals with the chemistry, construction, performance and modeling of the ultracapacitors.

4.2 Advantages of an ultracapacitor compared to a battery

Although batteries are the most widely used energy storage devices in distributed generation environments, ultracapacitors can be used in future due to the following advantages.

1. Ultracapacitors have very high power densities compared to the batteries.
2. Charging process in an ultracapacitor is very quick whereas fast charging in a battery may damage it.
3. The charge/discharge cycles in the ultracapacitor are high, generally in the range of hundreds of thousands of time. The batteries are capable of only a maximum of one or two thousands of cycles.
4. It has unlimited number of charge and discharge cycles.
5. The ultracapacitors can operate at very low temperatures of the order of -40°C whereas the batteries fail to operate if the temperature drops below -10°C.
6. The ultracapacitor can be totally discharged without impacting its performance whereas there is a limit on the voltage level up to which a battery can be discharged.
7. There are no degrading components in the ultracapacitors, which makes its maintenance easier compared to batteries.

4.3 Disadvantages of ultracapacitors

Ultracapacitors have certain disadvantages which are as listed below:

1. Specific energy is very small compared to that of the batteries.
2. Unlike batteries, it cannot supply energy for a long duration and therefore used only in short-term storage applications.
3. Cost of the ultracapacitor modules that are available in markets now is very high compared to even the most advanced battery.

4.4 Ultracapacitor principle and operation

4.4.1 Cell construction:

Figure 4.1 shows the basic construction of the ultracapacitor cell. Similar to the construction of the battery, it also has two electrodes immersed in an electrolyte. But the difference lies in the material with which the electrodes are made as well as the material used as the electrolyte. The electrodes of the ultracapacitors are generally made up of porous, high surface area particles. This increase in surface area results in an increased amount of ion absorption, which in turn results in the high power densities of the cells. The electrolyte is impregnated in between the anode and the cathode and is responsible for the movement of ions from one electrode to the other. The electrolytic solution is either potassium hydroxide or sulfuric acid. There is a thin membrane in between the electrodes called the separator. The main purpose of the separator is to prevent the electrodes from touching each other but allow the flow of ions between them. Both the anode and the cathode are lined by current collectors, the purpose of which is to assure a proper interface between the electrodes and the external connections [1].

Based on the type of material that is used for each electrode, the ultracapacitor can be classified as either symmetrical or asymmetrical. In symmetrical capacitors, both the electrodes are made of the same material, which is usually carbon. In the asymmetrical type of capacitors, which are the newest types, the electrodes are made up of different materials. Carbon is used for one electrode and Nickel hydroxide is used for the other. This is done mainly to make the charges on both the sides of the capacitor unequal thereby increasing the energy density and decreasing the leakage current.

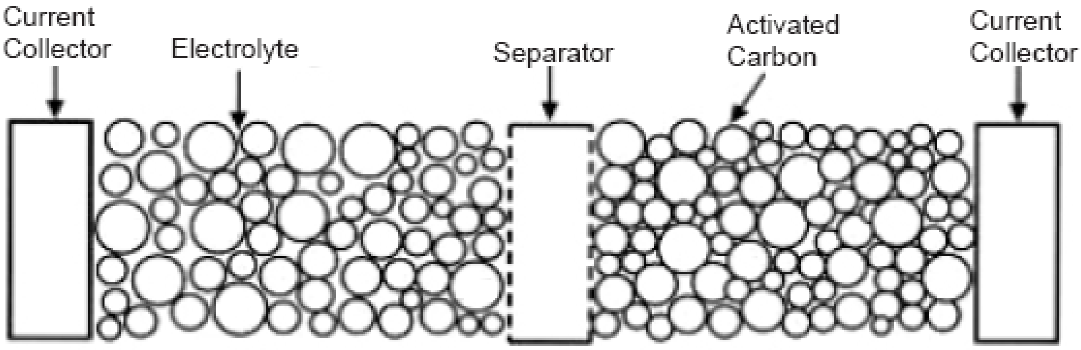

Figure 4.1 Construction of an ultracapacitor cell [7]

4.4.2 Working principle of the cell:

Storage mechanism in the ultracapacitors is by means of transfer of energy between the electrodes and the electrolyte [2]. When a voltage is applied, an electric field gets created between the electrodes. As a result of the generated electric field, an absorption layer is formed on the activated carbon electrodes. The charging and discharging of the ions takes place in this absorption layer. The charged ions migrate towards the oppositely charged electrodes through this layer. The charge or discharge time depends on the physical structure of the cell and is generally in the order of a few microseconds. The energy stored in the cell is given by the following equations:

Energy (Joules) $= \frac{1}{2}$ * Capacitance (Farad) *Voltage^2 (Volts) (4-1)

Energy (Watt hour) = Energy (Joules) / 3600 (sec) (4-2)

The amount of electrical energy that is stored in the capacitor depends on the following three factors [7]:

1. Surface area of the electrodes – the greater the surface area the greater is the amount of energy stored in the capacitor.
2. Distance between the electrodes – the amount of energy that can be stored varies directly with the distance between the electrodes.
3. Dielectric constant of the material used for the separator.

Most of the commercially available ultracapacitors have specific energy densities of about 5Wh/kg and specific power densities of about 20 kW/ kg. The voltage level of the ultracapcitor is about 2.5V to 2.7V per cell. The internal resistances of the ultracapacitors are very low compared to the batteries, thereby resulting in higher power densities than the batteries.

4.4.3 *Cell characteristics:*

Charging:

The ultracapacitors can be charged by either the constant current method or the constant power method.

- Constant current charging – The ultracapacitor is charged by a constant current input from the converter. The converter chosen can be either a buck or a boost converter. In most of the applications a buck converter is preferred because of the continuous output charge current.

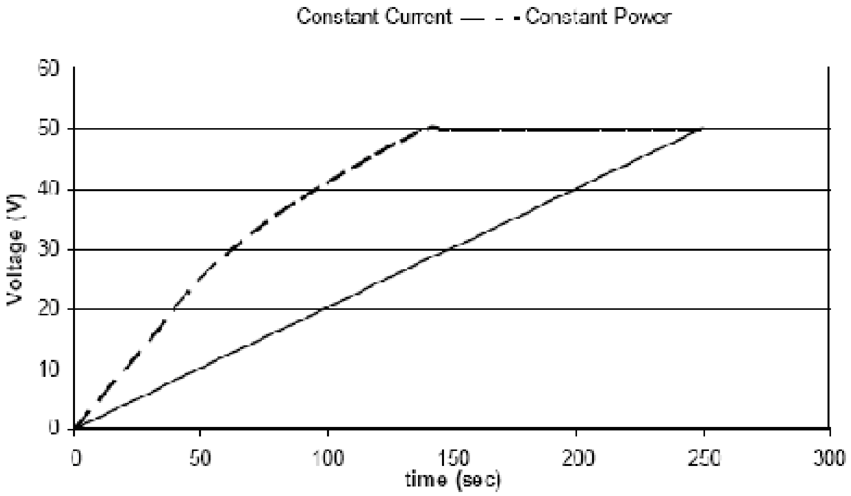

Figure 4.2 Charging times for the constant current and the constant power methods [3]

- Constant power charging – In this method current from the source is drawn at a constant voltage and used for charging the ultracapacitors. This method transfers all the available charge from the source to the ultracapacitors quickly. When compared to a constant current charging method, the time taken for charging in a constant power method is much higher. Figure 4.2 shows the time taken to charge the ultracapacitor by constant current as well as constant power charging.

Discharging:

Figure 4.3 gives the discharge profile of the ultracapcitor at a constant current [4]. In the graph, Vt represents the terminal voltage of the ultracapacitor and Td represents the discharge time. The figure shows the impact of the capacitive as well as the resistive components on the discharge voltage curve of the ultracapacitor. The operating voltage drops steeply initially, due to the equivalent series resistance after which the decrease in the voltage is gradual as a result of the capacitive element in the circuit. The time taken by the voltage to reach a minimum operating voltage is said to be the discharge time of the ultracapacitor.

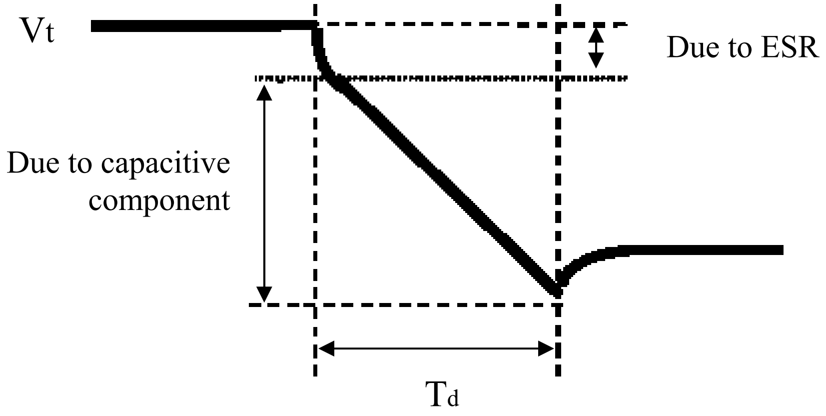

Figure 4.3 Discharge curve of an ultracapacitor

4.5 Equivalent circuit model of the ultracapacitor

There are a lot of circuit models that have been used in studies earlier, which include both simple as well as complex models. Depending on the requirement of the application, the complexity of the model is selected. The components of the circuit are selected depending on the required complexity. Similar to the battery, a first order model of the ultracapacitor is selected to be used in the study. The model that has been selected represents only the electrical properties of the cell and neglects most of the chemical properties. Figure 4.4 shows the equivalent circuit of the ultracapacitor [6].

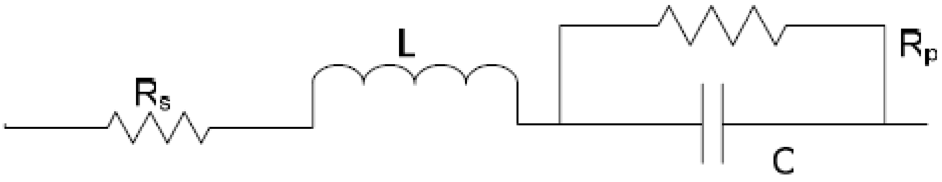

Figure 4.4 First order model of an ultracapacitor

4.5.1 Circuit elements:

The model has four main components, a capacitor C, inductor L, two resistors R_s and R_p which are in series and parallel respectively.

- The value of the capacitor, C, is chosen mainly based on the current and the voltage ratings of the ultracapacitor.
- The resistor R_p is used to represent the leakage current, which is usually in the range of a few milliamps.
- Resistance R_s is called the equivalent series resistance and contributes to the loss in energy of the ultracapacitor both during charging and discharging.

- The value of the inductor is generally small and negligible but in applications, which involve frequent charging and discharging, it is of significant value.

Apart from the circuit elements, the state of charge (SOC) of the ultracapacitor also needs to be considered while modeling the circuit.

4.5.2 Circuit equations

Based on the model in figure 4.4 the equations of the circuit are developed and used for modeling the ultracapacitor based on reference [6]. The major current and voltage equations that are used are as given below.

$$V_{cap} = V_c - (R_s * I_{cap}) - \left(L * \frac{di}{dt}\right) \tag{4-3}$$

$$V_c = V_{ci} - \left({}^{1}/_{C} * \int I_c \, dt\right) \tag{4-4}$$

$$I_c = I_{cap} + I_L \tag{4-5}$$

$$I_L = {}^{V_c}/_{R_p} \tag{4-6}$$

$$SOC = 1 - \left({}^{1}/_{Q_{rated}} * \int I_{cap} \, dt\right) \tag{4-7}$$

where:

V_{cap} = Operating voltage of the ultracapacitor (V)

V_c = Voltage across the capacitor (V)

V_{ci} = Initial voltage across the capacitor (V)

I_{cap} = Ultracapacitor current (A)

I_c = Current through the capacitor (A)

I_L = Current through the parallel resistor (A)

Q_{rated} = Rated maximum capacity of the ultracapacitor (Ah)

SOC = State of charge of the ultracapacitor

4.6 Sizing of ultracapacitors

The nominal voltage of an individual ultracapacitor is usually between 2.5 and 2.7V. In order to obtain the required higher voltage and power levels a number of cells are connected in series and in capacitance. The total number of capacitors that need to be connected in order to obtain the required voltage level is calculated using the power requirements of the load. The total capacitance and resistance values of the ultracapacitor bank are obtained as given below:

$$C_{tot} = \frac{C_c * N_p}{N_s} \tag{4-8}$$

$$R_{tot} = \frac{R_c * N_s}{N_p} \tag{4-9}$$

where:

C_{tot} and R_{tot} are the total capacitance and resistance of the bank,

C_c and R_c are, the capacitance and resistance of the individual ultracapacitor cells,

N_s and $N_p$are, the number of cells in series and parallel respectively.

The total voltage of the bank is obtained by just multiplying the voltage per cell of the ultracapacitor by the number of cells that needs to be connected.

$$V_{bank} = N_s * V_{cap} \tag{4-10}$$

where,

V_{bank} is the voltage of the bank and V_{cap} is the voltage level of the individual cell.

4.7 Simulink model of the ultracapacitor

Based on the first order model and the corresponding equations that were presented in the earlier sections, a model of the ultracapacitor is built in Simulink using the control system components in the Simulink library. The voltage level of the ultracapacitor can be increased or decreased by just changing the values of the capacitance and resistance and also the number of cells in series and in parallel.

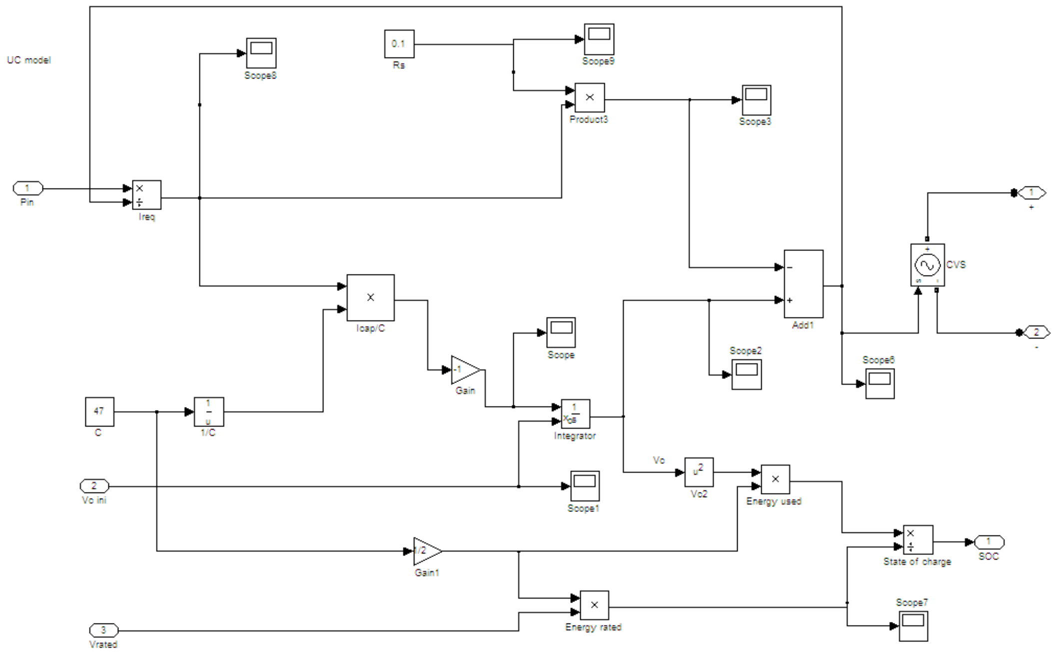

Figure 4.5 Model of the ultracapacitor developed in Simulink.

Figure 4.5 shows the model that has been developed in Simulink. The output that is obtained from the model is a signal output that cannot be connected directly to a power system component. Therefore the signal that is obtained is connected to the controlled voltage source, which in turn is connected to the required power system component.

4.8 Summary

In this chapter the modeling of ultracapacitors in Simulink was presented. The equivalent circuit used for modeling was explained and the necessary equations obtained from the circuit were also presented. Using the equations, a model of ultracapacitor was built in Simulink, which will be used in the technical analysis.

4.9 References:

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CHAPTER V

TEST SYSTEM MODELING IN MATLAB/ SIMULINK

5.1 Introduction

This chapter deals with the modeling of the test system that has been used for the research. The characteristics of the test system and its components are explained. Different power electronic interfaces for connecting the storage devices to the AC system are also presented. In this research there are certain indicators selected for the transient stability analysis. These indicators have been explained in this chapter. In the analysis, there are three different scenarios of load and generation that has been considered. Each of these test scenarios and the procedure to analyze the transient stability has also been explained.

5.2 Description of the test system

The model of the system that is used for the study must be carefully chosen based upon the application. The size of the system plays a vital role in the transient stability analysis. The system should not be too small since it would limit the number of scenarios that can be considered. This could actually lead to neglecting conditions that might have an influence on the stability thereby influencing the results obtained. On the other hand systems of very big size must also be avoided as they increase the time and complexity of the simulation. Based on the above factors an eight-bus system was selected for the study. A one-line diagram of the test system is shown in Figure 5.1 and the characteristics of the system are given in Table 5.1.

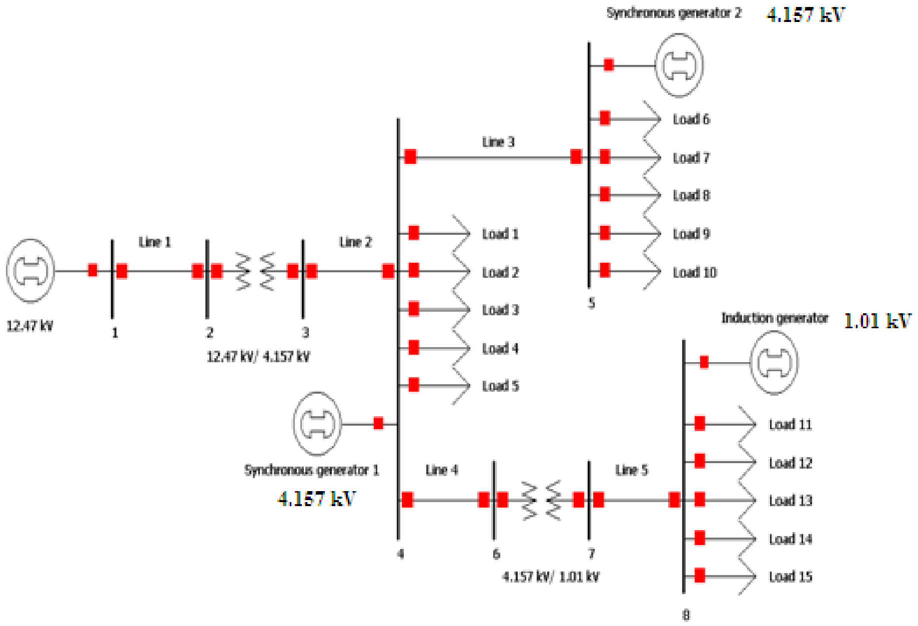

Figure 5.1 One-line diagram of the test system

As it can be seen from Figure 5.1, the test system consists of a main source and three distributed sources. Two of the distributed generators are connected to load buses 4 and 5 where the operating voltages are 4.157 kV each. The third generator is connected to bus 8, which has a lower voltage level of 1.01 kV.

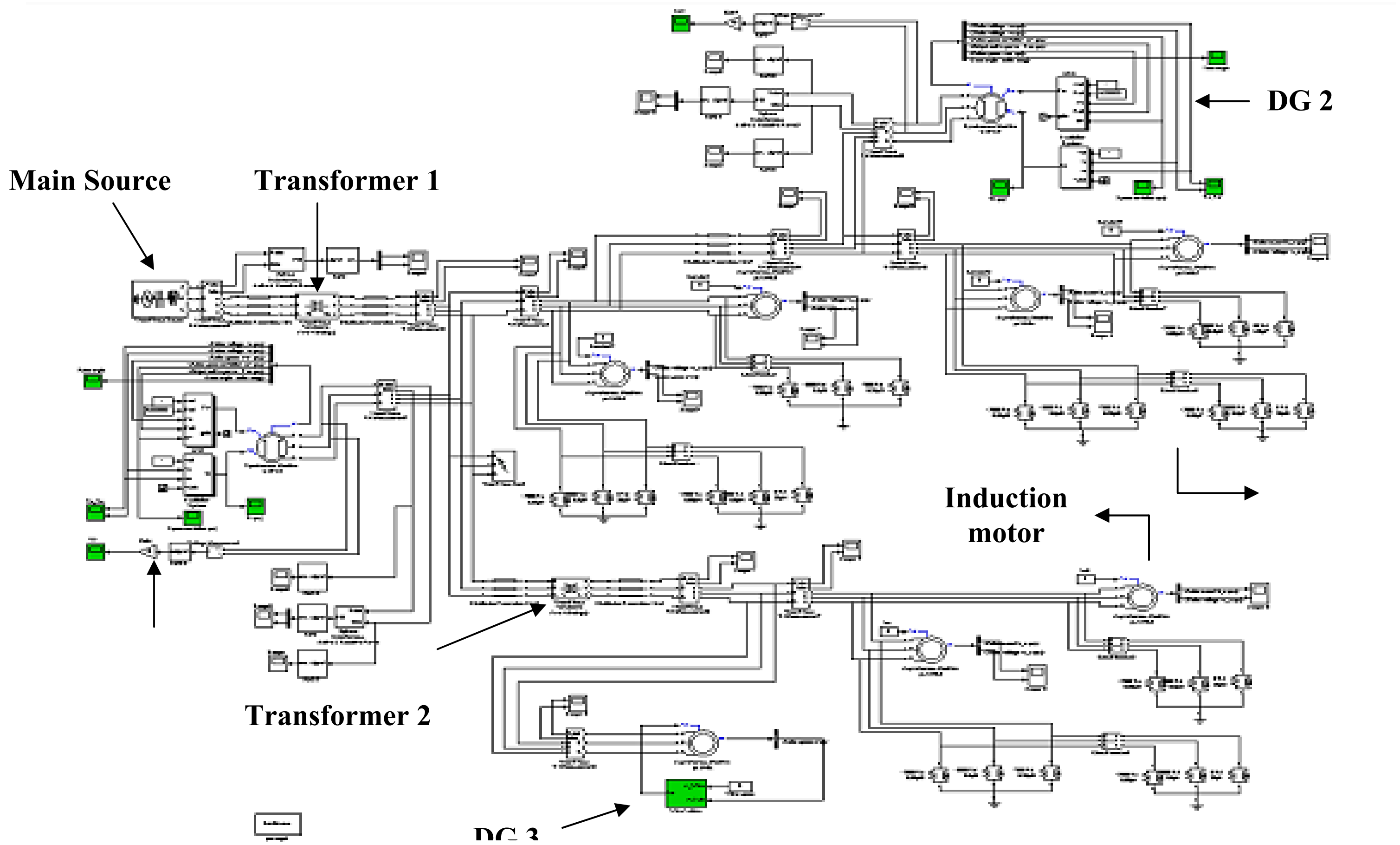

Figure 5.2 Eight-bus test system in Simulink

Table 5.1 Characteristics of the test system

System characteristics	*Value*
Total number of buses	8
Total number of sources:	4
– Main source	1
– Distributed sources	
o Squirrel cage Induction generator	1
o Synchronous generator	2
Number of loads:	15
– RL loads	9
– Induction motors	6
Total number of transformers	2

Figure 5.2 shows the test system that was built in Simulink using the power system components. Description of different components that are used in the system is given below:

Distributed generators:

Each distributed generator use a specific type of generator as an interface to the grid. For instance a biomass generator generally uses a synchronous machine whereas wind turbines generally use induction generator. Therefore both these types of generators have been selected to be used in the study. Two synchronous generators are connected to the system, one at bus 4 and another at bus 5. Both these generators operate at a voltage level of 4.157 kV. A squirrel cage induction generator is connected at bus 8, where the voltage level is 1.01kV.

Standard built-in models of governors and exciters of the generators are used from the power systems library in Simulink.

Loads:

The total load of the system is 45 MVA. In this study two types of loads are used which are simple RL loads and induction motors. The number of loads connected to each of the load bus depends upon the simulation scenario, which will be discussed in the next chapter.

Transformers:

There are two Y-Y transformers in the system. The first one steps down the voltage of 12.47kV at the main source to 4.157 kV at bus 4. The second transformer steps down the 4.157 kV at bus 4 to 1.01 kV at bus 8.

5.3 Power electronic interface

Both the battery and the ultracapacitor are DC devices and therefore they need suitable power conditioning devices to be interfaced with the AC system. It has been already mentioned that the energy storage devices discharge the stored energy at times when the load is unmet by the distributed generators. During this period the DC power from the storage devices needs to be converted into AC power in order to be able to supply the load. On the other hand, when there is enough power to supply the loads, the AC power from the grid is used to charge the storage devices.

Figure 5.3 represents the process of interconnecting the storage devices to the system using unidirectional and bidirectional converters.

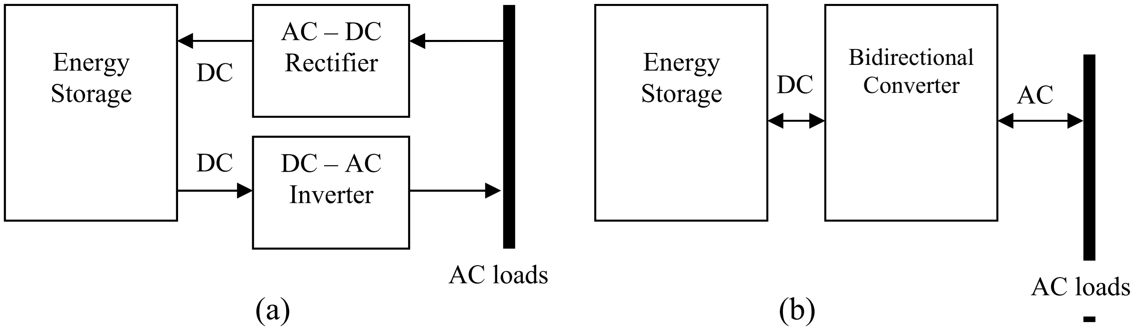

Figure 5.3 (a) Unidirectional and (b) bidirectional converter

In practical applications, the energy storage device is connected to the system by means of bidirectional converters since the cost of using two different converters is high. A bidirectional converter acts as both a rectifier and an inverter based on the direction of current flow. The basic scheme of a energy storage interface system is shown in figure 5.4.

In the scheme presented in figure 5.4, the energy storage system is connected to the grid through the voltage source inverter and a DC link capacitor. The energy storage device is connected at the DC side of the converter. The general working principle of the converter is as below:

- When the power demand from the grid is lesser than the power generated by the DG, the storage device absorbs power and is therefore charged.
- When the power demand is more than the power delivered by the DG, the storage device supplies the additional power that is needed.

The voltage source converter is controlled by means of two proportional-integral (PI) controllers in order to maintain the terminal voltage at the AC side of the converter at the required level. The model of a PWM IGBT inverter that is present in the Simulink library is shown in Figure 5.5. This model of converter is used in the study with certain modifications.

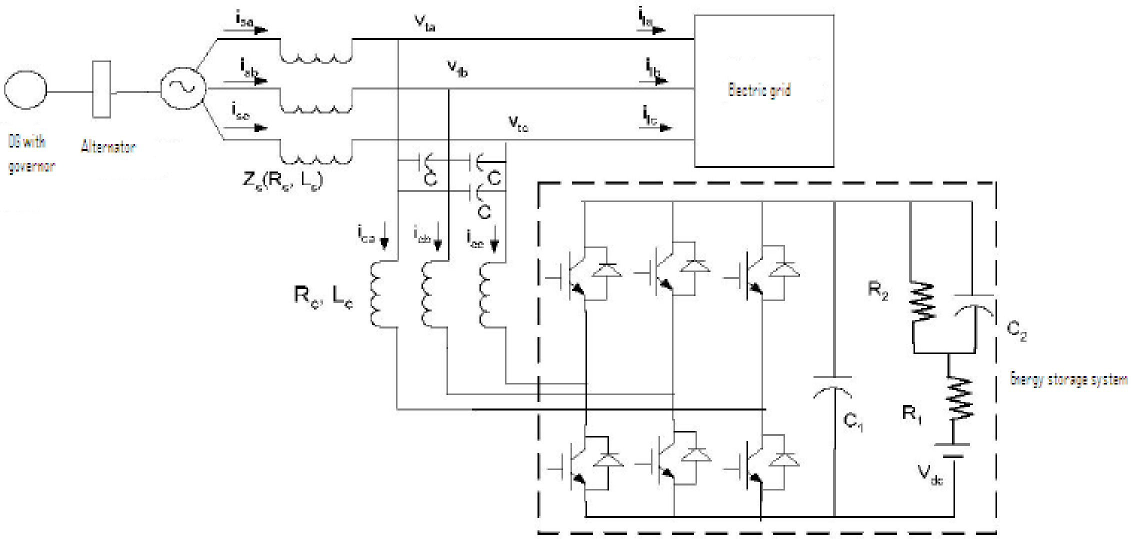

Figure 5.4 Interconnection scheme for storage devices [2]

The battery and ultracapacitor models that have been developed in Simulink are connected to the DC side of the converter, the AC side of which is connected to the system.

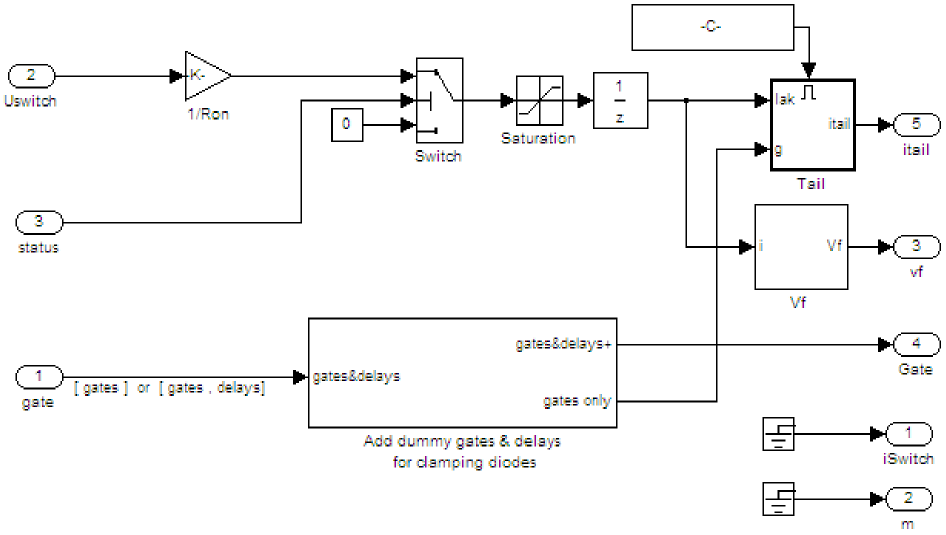

Figure 5.5 PWM based IGBT inverter [3]

5.4 Transient stability analysis of the system

Transient stability of a system is defined as the ability of the system to return back and remain in its stable operating condition following a severe disturbance. In order to analyze the transient stability of the system certain stability indicators were chosen by means of which the stability of the system was accessed. The description of these indicators, different scenarios that were considered for the analysis and the procedure to analyze stability is explained in this section.

5.4.1 Transient stability indicators

In order to investigate the transient stability of the test system, certain indicators have to be selected which indicate stability. The indicators selected depend upon the type of stability that needs to be monitored. In this research the four different stability indicators are selected based on references [4, 5 and 6]. The indicators selected are described below:

1. Rotor speed deviation

Rotor speed deviation can be defined as the maximum change in the speed of the rotor of the machine when a disturbance is applied to the system. The degree of stability is analyzed based on the amount of deviation in the speed. The stability of a system in which the rotor speed deviation is less is considered better than a system in which the speed deviation is more. Figure 5.6 shows the rotor speed deviation of a machine during fault.

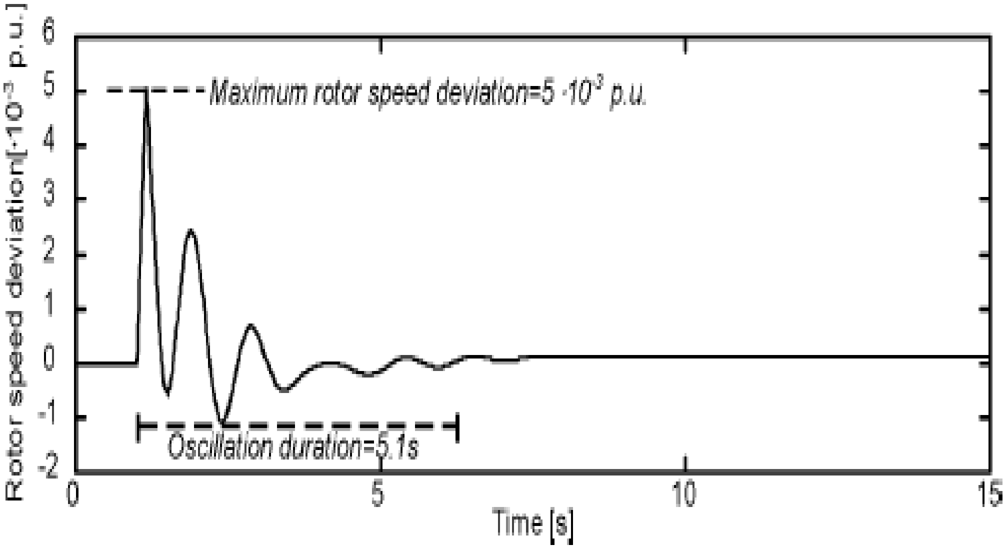

Figure 5.6 Rotor speed deviation and oscillation duration of a machine [4]

2. Oscillation duration

*"Oscillation duration is equal to the time interval between the application of the fault and the moment after which the rotor speed stays within a bandwidth of 1*10^-4 p.u during a time interval longer than 2.5 seconds"* [6]. The typical oscillation results of a machine are shown in Figure 5.6.

3. Rotor angle

Another parameter that indicates the angle stability of the system is the rotor angle of the machine. The rotor angle increases when a disturbance is applied and returns back to normal once the disturbance is cleared. This increase in the value of rotor angle is measured and based on it, the stability is assessed.

4. Terminal voltage

It is known that the voltage magnitude or phase of the system changes when there is a disturbance in the system. When a disturbance is applied to the system, the terminal voltage changes and when the fault is cleared it returns back to normal. A system is said to have better voltage stability if this change in voltage is less.

5.4.2 Test scenarios

Once the transient stability indicators are selected, the next step is to decide the different test scenarios that have to be considered. Before deciding the scenarios, the factors that influence the transient stability of a system must be noted. The major factors influencing the transient stability of the system are the type and location of the fault and the type of system considered. Different types of systems include equal and unequal load and generation conditions.

1. Case I - Equal generation and equal load

In this case, all the DG's are considered to supply an equal amount of power to the load. Based upon the penetration level of the DG that is considered, the power delivered by each of the generators is divided. Similarly the loads at each of buses are taken to be equal. Since the total load of the system is 45MVA, the load at each of the bus is taken to be 15 MVA.

2. Case II - Equal generation and unequal load

This case takes into account equal amounts of power delivered by the DG's with unequal amounts of loads at each of the load buses. Similar to the previous case, based upon the penetration level of the DG, the power delivered by each of the generator is divided. The load at bus 4 is considered to be higher than the other two buses. The load at bus 4 is 60% (27MVA) and those at bus 5 and 8 are 20% (9MVA) each.

3. Case III - Unequal generation and equal load

This case considers equal loads (15MVA each) at all the buses are considered equal. DG 1 which is connected to bus 4 is considered to supply 50% of the required penetration level and DG 2 and 3, which are connected to buses 5 and 8, are considered to supply 25% of the penetration level each. In each of the cases different types and locations of faults and different penetration levels of DG are considered. Three different fault types namely L-G, L-L-G and three phases are considered. Similarly three different locations of faults namely bus 4, bus 5 and bus 8 are considered. In each case 10 different penetration levels (from 5% to 50%) of the DG are considered. Penetration level of the DG is defined as the percentage of load that is supplied by the distributed generators which is as given below:

$$\text{Penetration level of DG} = \frac{\sum P_{DG}}{\sum P_{load}} * 100 \tag{5-1}$$

where:

P_{DG} = Total power delivered by all the DG's together

P_{load} = Total load demand

Table 5.2 gives an overview of the different scenarios considered. An explanation of each of the scenarios is given below.

Table 5.2 Different test scenarios for transient stability analysis

Test scenarios	*DG1 (Bus 4)*	*DG2 (Bus 5)*	*DG3 (Bus 8)*	*Load1 (Bus 4)*	*Load 2 (Bus 5)*	*Load 3 (Bus 8)*
Case I	Equal	Equal	Equal	15MVA	15MVA	15MVA
Case II	Equal	Equal	Equal	27MVA	9MVA	9MVA
Case III	50%	25%	25%	15MVA	15MVA	15MVA

5.4.3 Procedure for analyzing the transient stability

A step-by-step approach to analyze the transient stability of the system is given below:

- ☐ A fault is applied at a one of the three buses of the system as mentioned in the scenario. The duration of the fault is 100ms after which it is considered to be cleared automatically. The fault is applied at 1.5 sec and cleared at 1.6 sec.
- ☐ The penetration level of the DG is varied from 5% to 50%. The MVA of the generators is changed based on the penetration level.
- ☐ The response of the system to the fault is analyzed by means of the transient stability indicators that are chosen.
- ☐ This procedure is repeated for different types and locations of faults with different penetration levels of the DG.
- ☐ After the analysis without energy storage devices, the transient stability with energy storage devices needs to be done.
- ☐ The energy storage devices are connected to the system by means of the power electronic converter as explained in Chapter 5.
- ☐ About 10% of the DG power is considered to be supplied by the storage devices
- ☐ The process of analyzing stability is repeated as done earlier for the system without energy storage devices.
- ☐ The responses of the indicators to the fault are analyzed for the system with energy storage devices.

5.5 Summary

In this chapter the test system used for the study was introduced. The characteristics and components of the 8-bus test system were discussed. A brief description of the power electronic interface that is necessary to connect the storage devices to the system was also given. The four different transient stability indicators that were used in this study were explained. Finally the different scenarios in the analysis and the procedure for analysis were also explained.

5.6 References

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CHAPTER VI

SIMULATION RESULTS FOR TRANSIENT ANALYSIS WITH DISTRIBUTED GENERATORS

6.1 Introduction

The transient stability of the 8- bus test system is carried out as explained in the previous chapter. The analysis is done both with and without energy storage devices. The results of the simulation without storage are presented in this chapter.

6.2 Transient stability analysis without energy storage devices

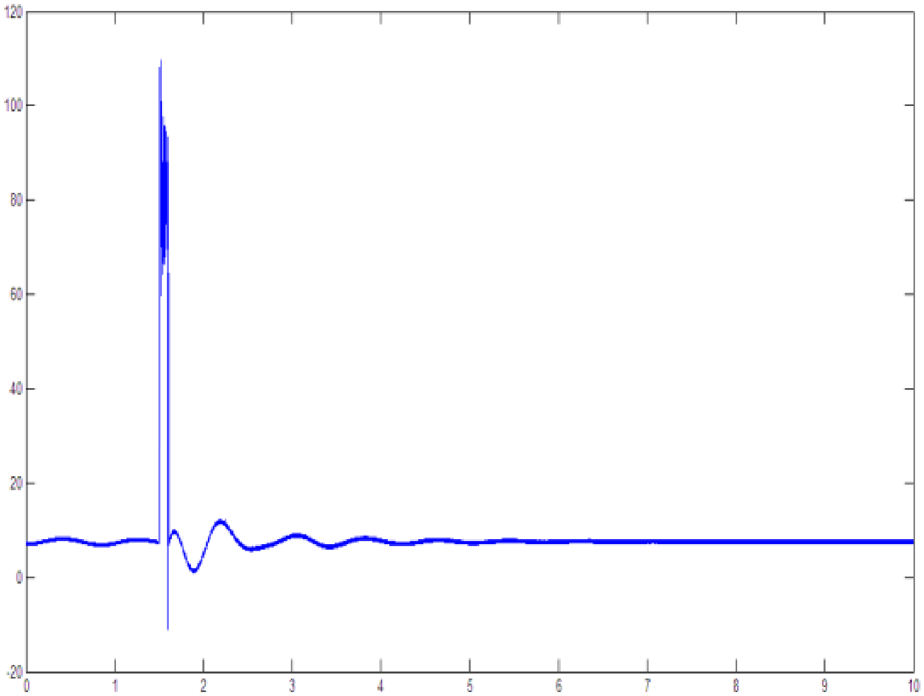
This section includes the transient stability study of the test system without any storage device. The responses of the four different indicators for all the three cases are presented below.

6.2.1 Case I - Equal generation and equal load conditions

The responses of the four different indicators to different types of faults and different penetration levels of the DG are analyzed for faults at buses 4, 5 and 8.

Rotor angle

When a fault is applied at 1.5 sec to the system, the rotor angle increases and assoon as the fault is cleared it drops back and settles to a constant value. Different penetration levels of the DG's are analyzed. An example of this can be seen in Figures 6.1 and 6.2, which show the deviation in rotor angle for a three phase fault with 10% and 50% penetration of the DG's, respectively.



Time (sec)

Figure 6.1 Change in rotor angle for faults at bus 4 with 10% penetration level of DG

A three-phase fault is applied to the system at bus 4. The fault is applied at the rotor angle changes to about 109 radians. Figure 6.2 shows the increase in rotor angle for the same three-phase fault but with 50% penetration level of the DG. In this case the change in rotor angle is only about 90 radians.

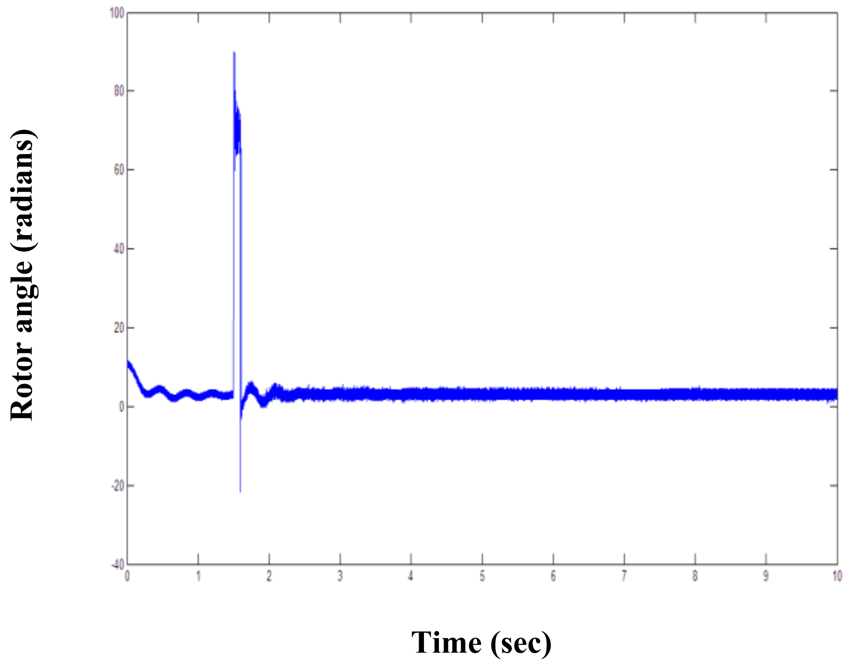


Figure 6.2 Change in rotor angle for faults at bus 4 with 50% penetration level of DG

Similarly the change in the rotor angle for the three types and locations of faults with the different penetration levels of the DG are analyzed. The results obtained are given in the bar graphs below.

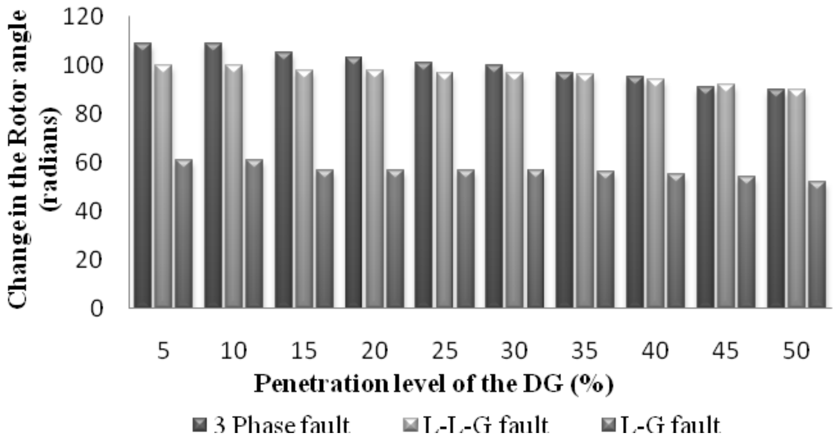


Figure 6.3 Rotor angle response for different faults at bus 4 (Case I)

The change in the rotor angle for different types of faults and penetration levels when the fault is at bus 4 can be seen in Figure 6.3. Similarly the results obtained when the fault is at bus 5 and bus 8 are given in Figures 6.4 and 6.5 respectively.

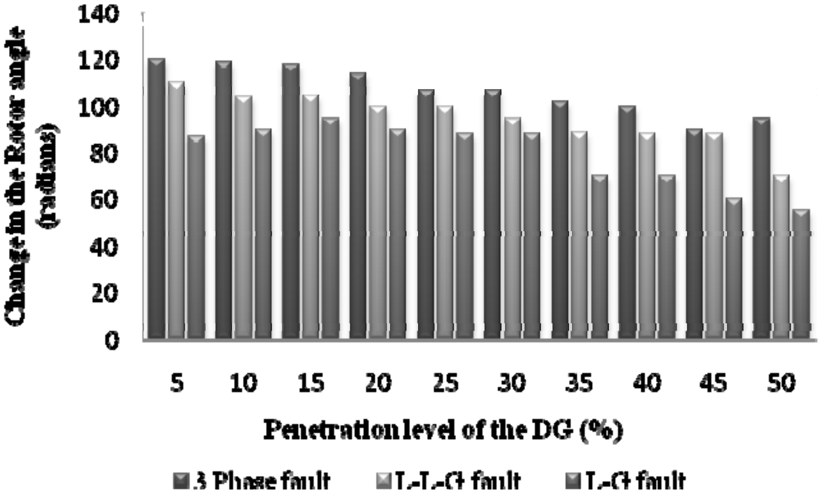


Figure 6.4 Rotor angle response for different faults at bus 5 (Case I)

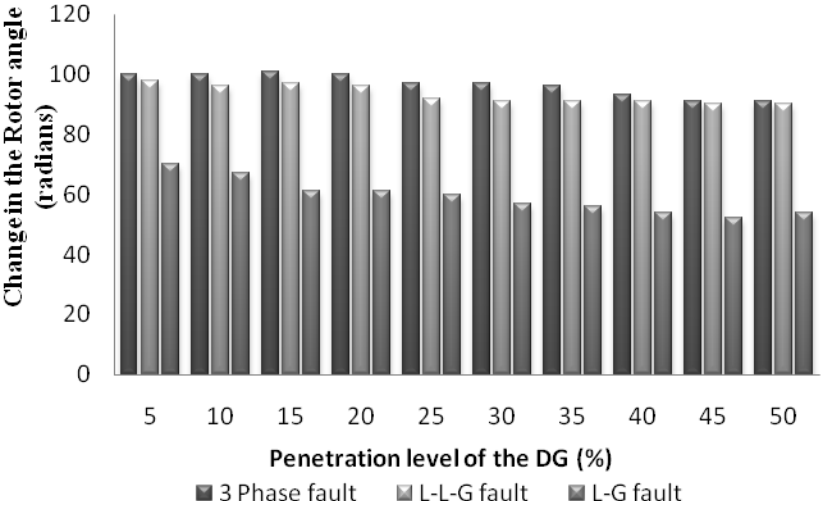


Figure 6.5 Rotor angle response for different faults at bus 8 (Case I)

In all the cases, the change in rotor angle decreases when the penetration level of the distributed generators is increased. This proves that the transient stability of the system improves with more penetration levels of the DG. The type and location of fault does not affect the transient stability.

Terminal voltage

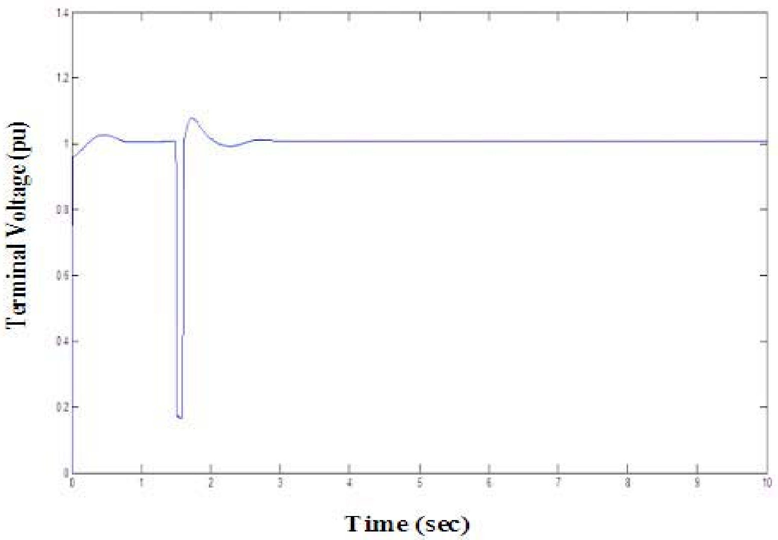


Figure 6.6 Drop in terminal voltage for faults at bus 4 with10% penetration level of DG (Case I)

Similar to the rotor angle, the drop in terminal voltage was also monitored for different penetration levels and different types of faults. An example of the response that was obtained for a three-phase fault is given in Figures 6.6 and 6.7. Figure 6.6 shows the drop in the terminal voltage when a three-phase fault is applied to bus 4 and with 10% penetration level of the DG. The drop is found to be about 0.85 pu. For a similar type and location of fault but with increased penetration level of the DG, the drop during fault is reduced to about 0.62 pu as seen in figure 6.7.

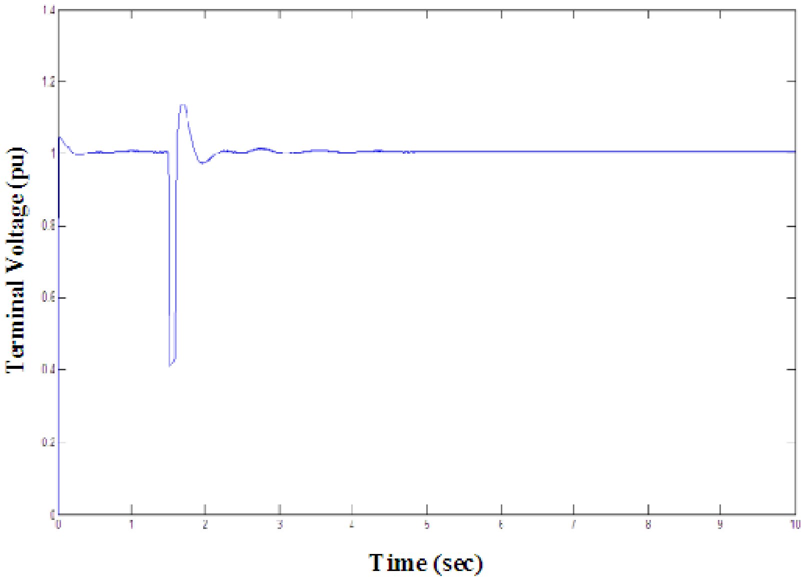


Figure 6.7 Drop in terminal voltage for faults at bus 4 with 50% penetration level of DG (Case I)

Similar responses were obtained for all the three types of faults. The response for all the types and location of faults and penetration levels are given in Figures 6.8, 6.9 and 6.10.

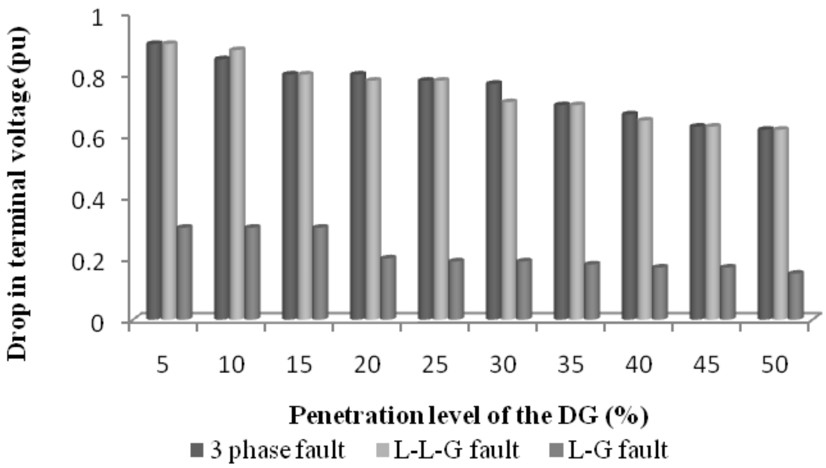


Figure 6.8 Terminal voltage response for different faults at bus 4 (Case I)

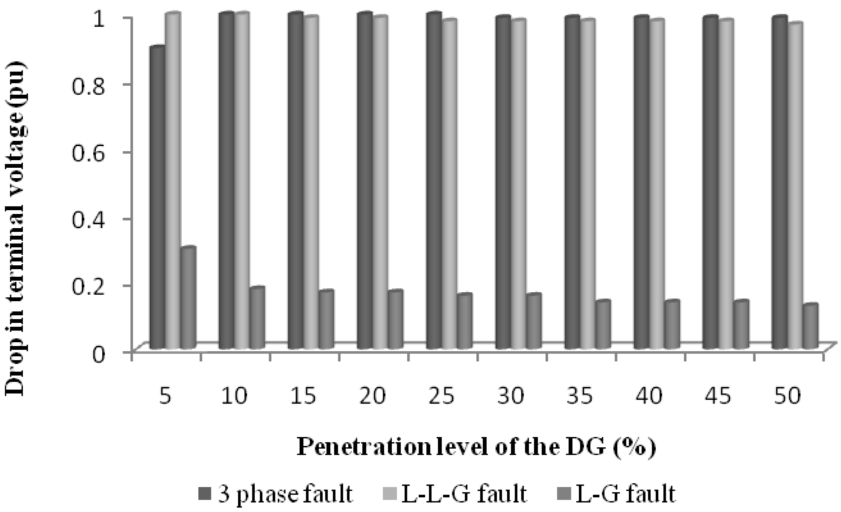


Figure 6.9 Terminal voltage response for different faults at bus 5 (Case I)

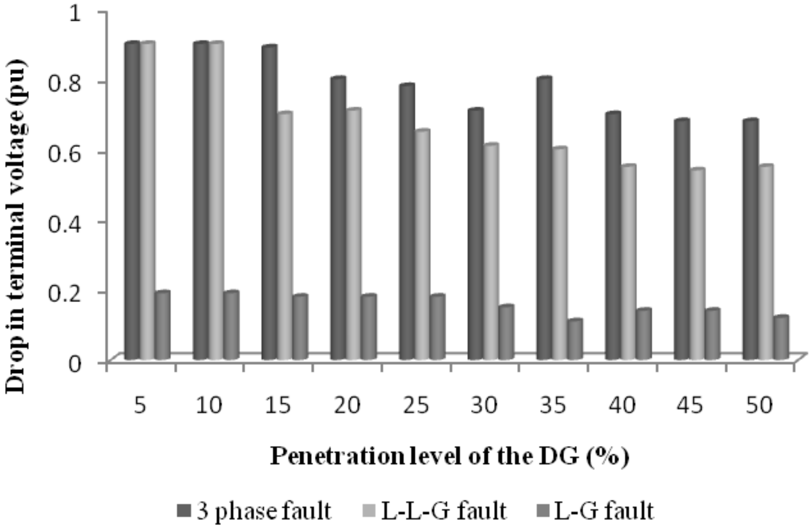


Figure 6.10 Terminal voltage response for different faults at bus 8 (Case I)

From the graphs, it can be seen that the drop in terminal voltage is more for a severe fault compared to a less severe fault. But in general, the drop in voltage decreases with increase in penetration level of the DG irrespective of the type and location of the fault.

The results that were obtained from the voltage analysis implies that the transient stability of the system gets better with increase in the penetration level of the DG.

Rotor speed deviation

The analysis of the rotor speed is done in a similar way as that of rotor angle and terminal voltage. Different types of faults are applied at three different buses and the maximum deviation in the rotor speed during the fault period is analyzed.

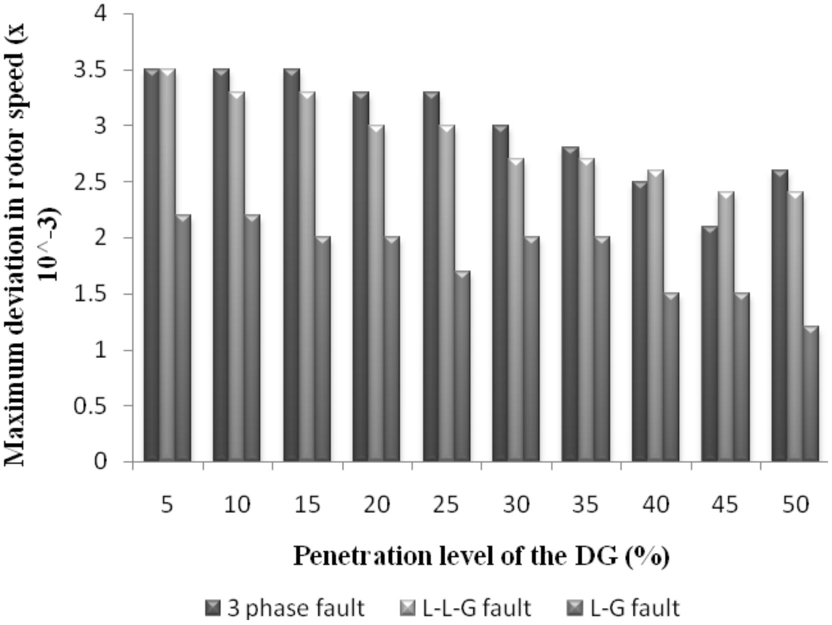


Figure 6.11 Rotor speed deviation for different faults at bus 4 (Case I)

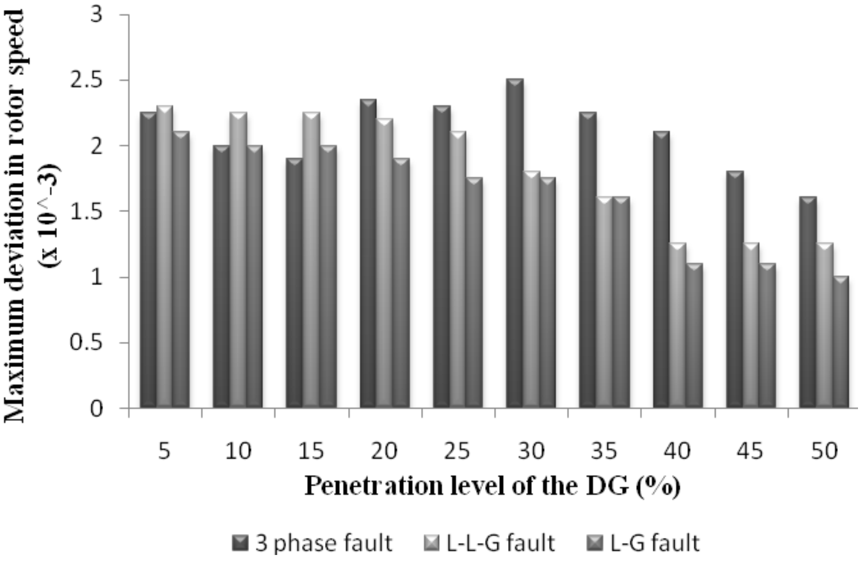


Figure 6.12 Rotor speed deviation for different faults at bus 5 (Case I)

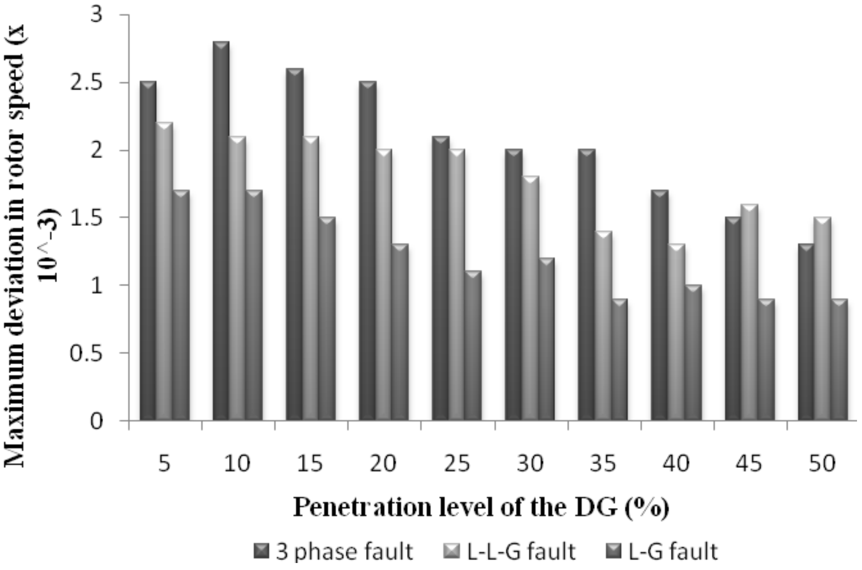


Figure 6.13 Rotor speed deviation for different faults at bus 8 (Case I)

Figures 6.11, 6.12 and 6.13, show the maximum deviation in rotor speed during fault for different types and locations of faults and different penetration levels of the DG. Similar to the previous two indicators, the maximum deviation in rotor speed during fault also decreases with more and more penetration of the DG. For instance, the maximum deviation in rotor speed for an L-G fault at bus 5 with 50% penetration level of the DG is reduced almost two times that with 10% penetration level. This is true for any type and location of the fault.

From the results obtained, it can be concluded that the increase in size of the DG improves the overall transient stability of the system. The type and location of the fault does not affect the relative transient stability.

Oscillation duration

As explained earlier, oscillation duration is the time taken for the oscillations to settle down to an acceptable level after the clearance of fault. When a fault is applied, the rotor speed starts oscillating and when the fault is cleared the oscillations start to settle. Depending upon the time taken by the oscillations to settle, the stability of the system can be assessed. The transient stability of the system keeps improving with increase in the penetration levels of the DG.

In Figure 6.14, it can be obsereved that the oscillation duration increases with the severity of the fault. For instance, the oscillation duration of rotor speed is more for a three phase fault compared to a L-G fault. But when we consider each type of fault separately, the oscillation duration is found to decrease with an increase in penetration level. This implies that increase in DG penetration level improves the stability of the system.

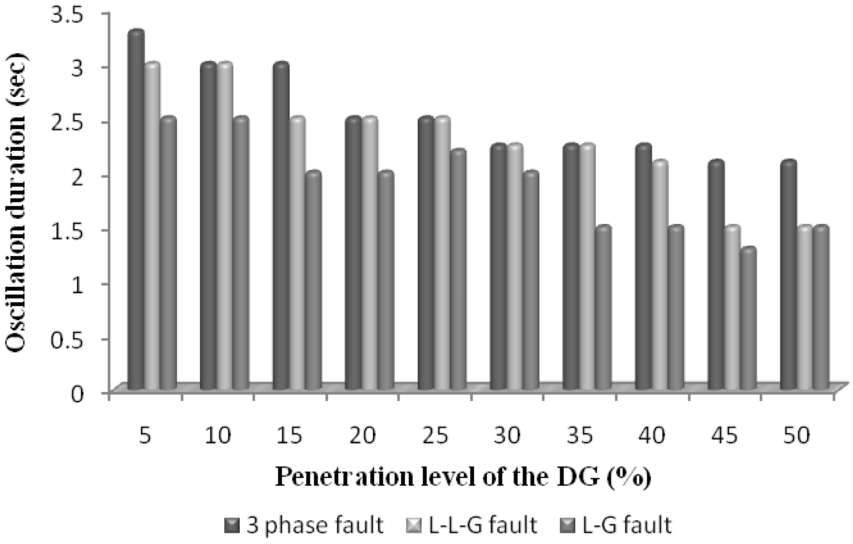


Figure 6.14 Oscillation duration for different faults at bus 4 (Case I)

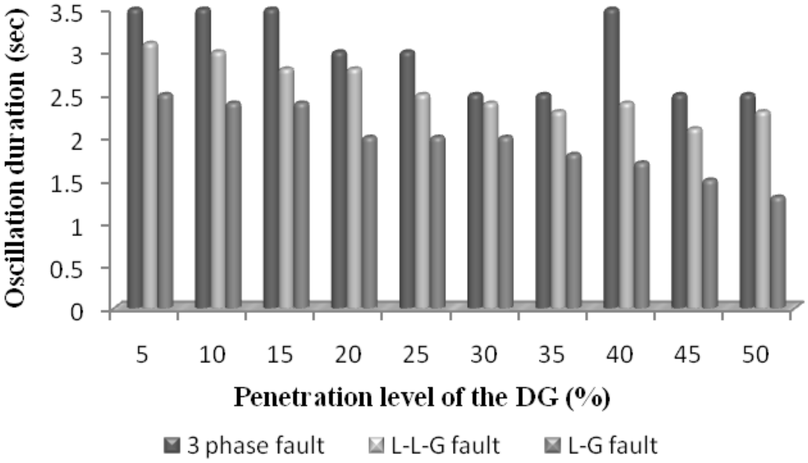


Figure 6.15 Oscillation duration for different faults at bus 5 (Case I)

Similar is the case for faults at bus 8 also. Figure 6.16 shows the oscillation durations for the three faults at bus 8.

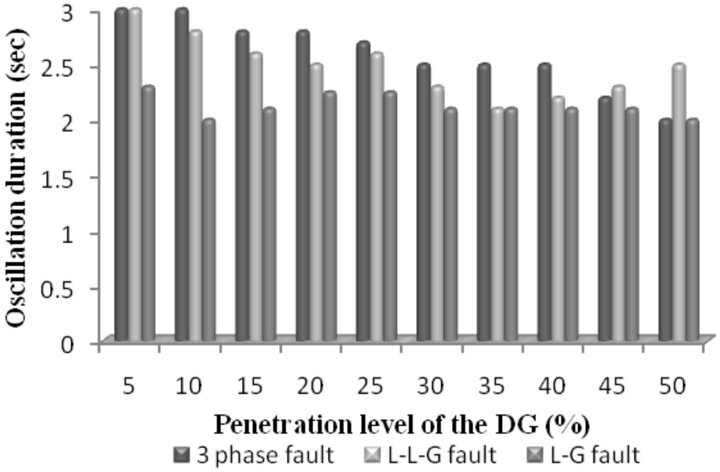


Figure 6.16 Oscillation duration for different faults at bus 8 (Case I)

6.2.2 Case II - Equal generation and unequal load conditions

In this case the DG's are considered to supply equal amounts of power to the loads, which are unequal. The results of the simulation are tabulated similar to the previous case are presented in this section.

Rotor angle

The response of the rotor angle to different types of faults with different penetration levels of the DG's are discussed here. Similar to case I, in this case also there was less change in the rotor angle during fault when the penetration of the DG was increased.

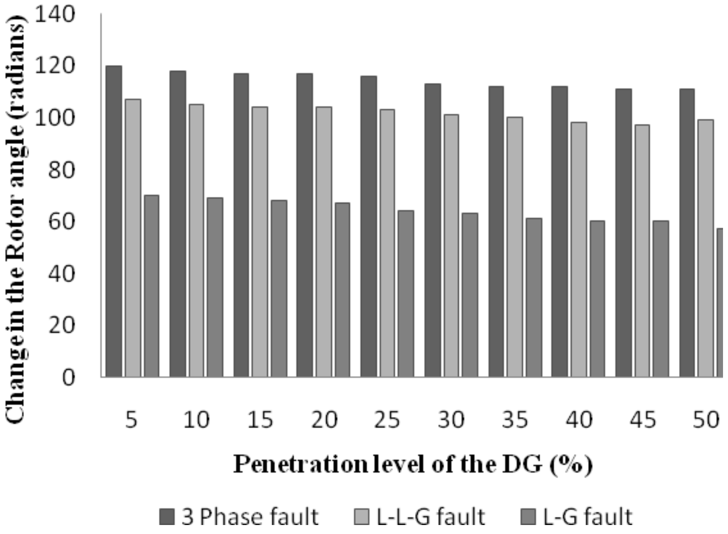


Figure 6.17 Change in rotor angle for different faults at bus 4 (Case II)

Figure 6.17shows the change in rotor angle for different fault types at bus 4 for 5% – 50% penetration levels of the DG. The only difference between cases II and I is in the amount change in rotor angle. For faults at buses 5 and 8 similar results were obtained which can be seen in Table 6.1 below.

Table 6.1 Deviation in rotor angle for faults at bus 5 and 8 in Case II

DG Penetration (%)	*Deviation in rotor angle when fault is at bus 5*			*Deviation in rotor angle when fault is at bus 8*		
	3 Ph	L-L-G	L-G	3 Ph	L-L-G	L-G
5	138	117	90	109	103	76
10	137	116	90	107	102	75
15	137	113	88	106	103	74

Table 6.1 (continued)

20	136	112	88	105	102	75
25	132	111	87	104	101	73
30	133	111	87	104	101	72
35	133	108	85	101	99	72
40	130	107	84	100	98	72
45	128	106	81	99	97	70
50	128	104	83	97	94	69

Terminal voltage

The drop in terminal voltage when a fault is applied is analyzed for case II similar to case I. The results that were obtained are tabulated and presented below.

Table 6.2 Drop in terminal voltage for different types and locations of faults for Case II

DG Penetration (%)	*Drop in pu terminal voltage when fault is at bus 4*			*Drop in pu terminal voltage when fault is at bus 5*			*Drop in pu terminal voltage when fault is at bus 8*		
	3 Ph	L-L-G	L-G	3 Ph	L-L-G	L-G	3 Ph	L-G	L-L-G
5	1.0	0.9	0.5	1	0.95	0.4	0.95	0.2	0.9
10	1.0	0.9	0.4	0.9	0.93	0.39	0.94	0.18	0.88
15	0.99	0.89	0.4	0.95	0.92	0.37	0.94	0.17	0.86
20	0.98	0.87	0.4	0.95	0.91	0.37	0.93	0.16	0.85

Table 6.2 (continued)

25	0.98	0.87	0.3	0.94	0.91	0.36	0.93	0.16	0.84
30	0.97	0.86	0.3	0.91	0.91	0.35	0.90	0.15	0.82
35	0.96	0.85	0.1	0.90	0.89	0.33	0.89	0.13	0.80
40	0.94	0.83	0.09	0.89	0.88	0.33	0.87	0.12	0.80
45	0.92	0.82	0.09	0.86	0.85	0.32	0.86	0.11	0.78
50	0.89	0.82	0.1	0.88	0.83	0.33	0.89	0.11	0.79

The drop in voltage due to the three types of faults namely 3phase, L-L-G and L-G is found to decrease as the percentage penetration of the DG increases.

Rotor Speed deviation

The maximum deviation in the rotor speed is monitored and analyzed for unequal load conditions with the same types and locations of faults. The impact of the rise in the penetration level of the DG's on this indicator is similar to all the other cases. The rotor speed deviation for L-G fault at bus 5 with 5% penetration level of the DG is shown in Figure 6.18.

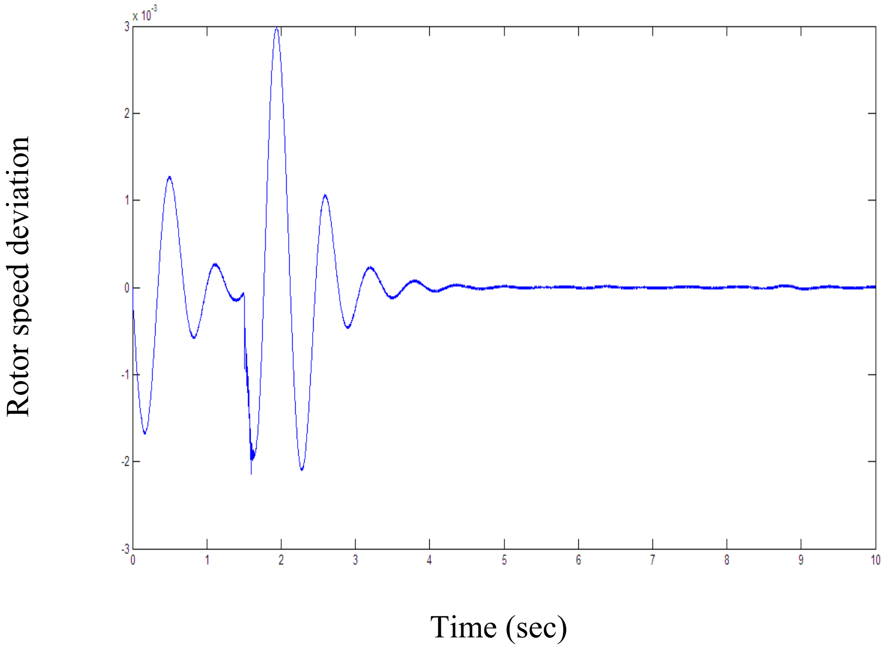


Figure 6.18 Maximum deviation in rotor speed for 3 phase fault at bus 8 with 5% DG (Case II)

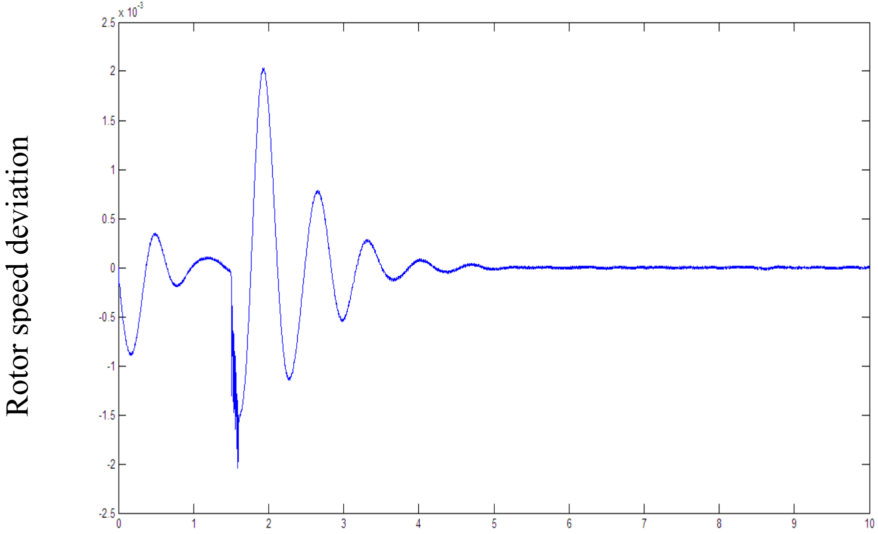


Figure 6.19 Maximum deviation in rotor speed for 3 phase fault at bus 8 with 40% DG (Case II)

From the figure it can be seen that when the fault is applied, the deviation in the rotor speed reaches. When a similar type of fault was applied with 50% penetration level of the DG, the deviation was observed to be lesser as shown in Figure 6.19.

Figures 6.20, 6.21 and 6.22 show the rotor speed deviation for different types of faults at three different locations with different penetration levels of the DG.

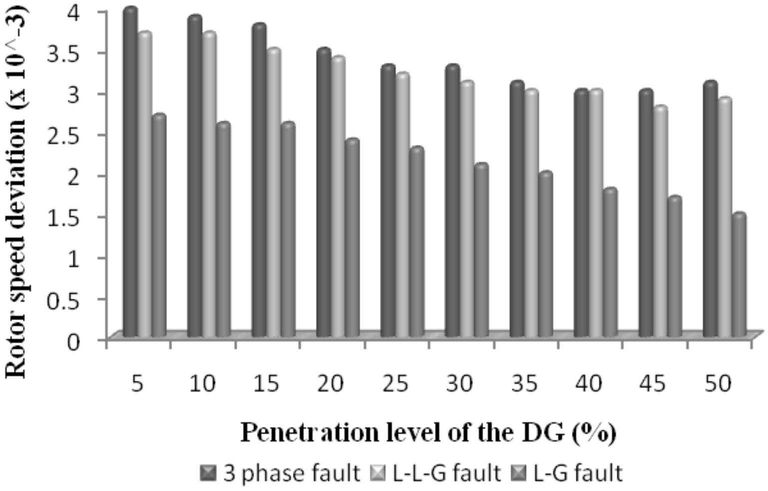


Figure 6.20 Deviation in rotor speed for different faults at bus 4 (Case II)

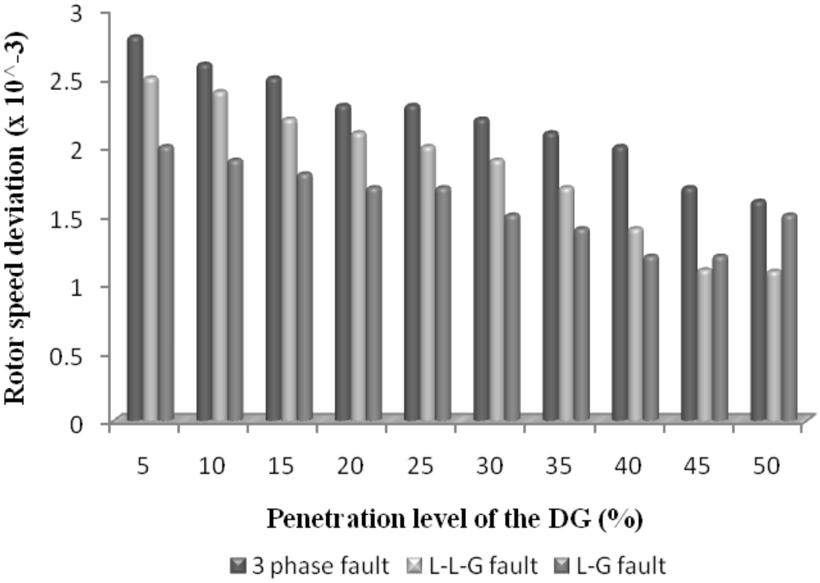


Figure 6.21 Deviation in rotor speed for different faults at bus 5 (Case II)

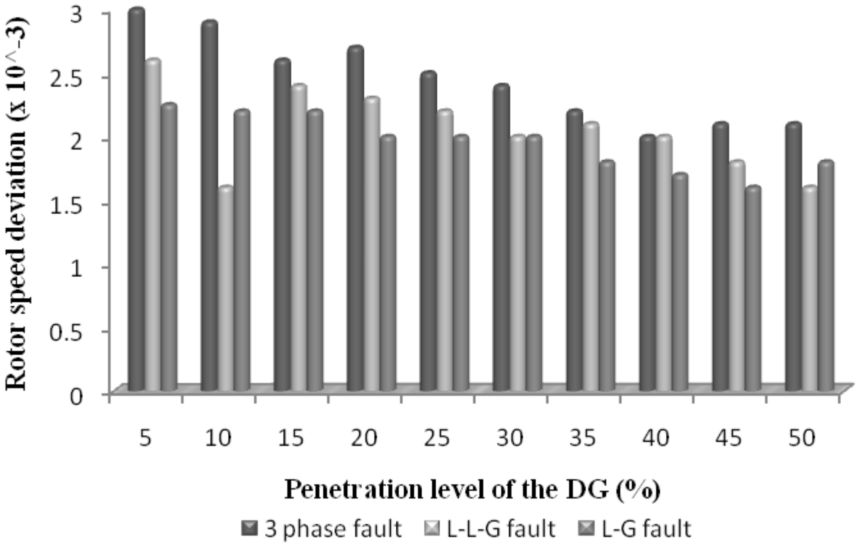


Figure 6.22 Deviation in rotor speed for different faults at bus 8 (Case II)

Oscillation duration

Similar to the previous indicators, the oscillation duration for case II was found to improve with the increasing penetration levels of DG.

Table 6.3 Oscillation durations for different types and locations of faults (Case II)

DG Penetration (%)	*Oscillation duration of rotor speed when fault is at bus 4 (sec)*			*Oscillation duration of rotor speed when fault is at bus 5 (sec)*			*Oscillation duration of rotor speed when fault is at bus 8 (sec)*		
	3 Ph	L-L-G	L-G	3 Ph	L-L-G	L-G	3 Ph	L-L-G	L-G
5	4.2	3.7	2.9	4.6	4	3.1	3.8	3.6	2.6
10	4.1	3.7	2.7	4.5	3.7	3.0	3.7	3.5	2.5
15	4.1	3.5	2.6	4.3	3.6	3.1	3.7	3.4	2.5

Table 6.3 (continued)

20	4.0	3.4	2.5	4.2	3.5	3.0	3.5	3.2	2.3
25	3.8	3.2	2.4	4.0	3.4	2.8	3.4	3.1	2.3
30	3.7	3.1	2.2	3.7	3.2	2.6	3.3	3.1	2.2
35	3.5	3.0	2.2	3.7	3.1	2.5	3.3	3.0	2.1
40	3.4	3.0	2.0	3.6	3.0	2.3	3.2	2.9	2.0
45	3.2	2.8	1.7	3.5	3.0	2.2	3.2	2.7	2.0
50	3.2	2.7	1.8	3.7	3.1	2.1	3.2	2.6	2.2

Though the time taken by the oscillations to settle down is higher compared to case I, the overall stability of the system is found to improve as in that case. Table 6.3 gives the time taken for the oscillations to settle down when the loads are unequal.

From the results obtained in case II, we see that there is improvement in the response of the system when the penetration level of the DG’s increase similar to case I. But the amount of deviations and oscillations are more in the second case compared to the former. Therefore change in the number of loads affects the overall stability of the system.

6.2.3 Case III – Unequal generation and equal load conditions

In this case the distributed generators are considered to supply unequal amounts of power to the loads, which are equally distributed at the load buses. The distributed generator at bus 4 is considered to supply more power than the remaining two DG’s. The results obtained for this case are discussed below.

Rotor angle

When we consider the three-phase fault for this case, the change in rotor angle is seen to be decreasing as the DG penetration level increases. But when we compare the results of case I and II for the same three-phase fault, we can see that the deviation in rotor angle has increased in case III. Though the transient stability in this case is seen to be improving with more DG penetration, it is poor compared to the previous two cases. The results that were obtained for case III are given in Table 6.4.

Table 6.4 Deviation in rotor angle for different types and locations of fault (Case III)

DG Penetration (%)	*Deviation in rotor angle when fault is at bus 4*			*Deviation in rotor angle when fault is at bus 5*			*Deviation in rotor angle when fault is at bus 8*		
	3 Ph	L-L-G	L-G	3 Ph	L-L-G	L-G	3 Ph	L-L-G	L-G
5	137	121	73	146	129	106	120	109	85
10	135	120	73	145	128	105	119	107	84
15	134	120	71	143	125	105	118	105	82
20	132	117	72	142	123	103	116	104	81
25	131	116	70	141	122	102	115	101	80
30	130	114	69	140	121	100	114	100	77
35	128	111	68	138	119	100	111	100	75

Table 6.4 (continued)

40	127	110	67	137	118	99	110	98	72
45	125	110	64	136	117	98	109	95	71
50	125	110	65	135	116	99	109	97	73

Terminal voltage

The conclusions from the response of the rotor angle in case III can be applied to the terminal voltage response for case III also. In this case too, though the performance of the system can be seen to improve, it is poor compared to the previous two cases. This can be observed from the results shown in Table 6.5.

Table 6.5 Drop in terminal voltage for different types and locations of fault (Case III)

DG Penetration (%)	*Drop in pu terminal voltage when fault is at bus 4*			*Drop in pu terminal voltage when fault is at bus 5*			*Drop in pu terminal voltage when fault is at bus 8*		
	3 Ph	L-L-G	L-G	3 Ph	L-L-G	L-G	3 Ph	L-L-G	L-G
5	1	0.9	0.6	1	1	0.5	1	0.95	0.27
10	1	0.9	0.6	0.98	0.99	0.47	0.97	0.95	0.25
15	0.99	0.89	0.6	0.97	0.99	0.45	0.96	0. 94	0.24
20	0.99	0.88	0.45	0.97	0.97	0.44	0.95	0.92	0.22
25	0.98	0.85	0.45	0.97	0.97	0.41	0.94	0.91	0.21
30	0.97	0.84	0.35	0.96	0.97	0.38	0.91	0.90	0.21

Table 6.5 (continued)

35	0.97	0.82	0.3	0.96	0.96	0.36	0.90	0.87	0.20
40	0.95	0.81	0.27	0.95	0.95	0.35	0.87	0.86	0.18
45	0.93	0.80	0.25	0.96	0.95	0.32	0.85	0.84	0.15
50	0.92	0.83	0.26	0.96	0.96	0.35	0.83	0.85	0.15

Rotor speed deviation

The deviation in rotor speed for unequal generation and equal load case for different types and locations of faults is given in Figures 6.23, 6.24 and 6.25.

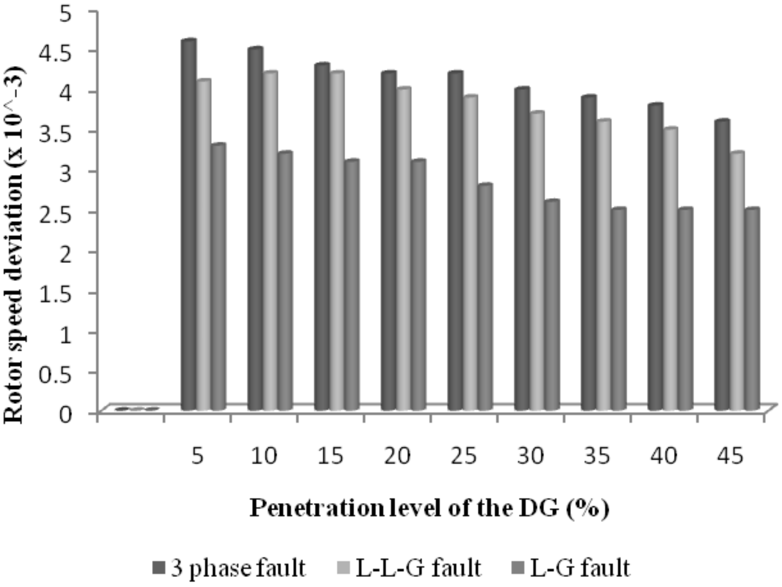


Figure 6.23 Rotor speed deviation for different faults at bus 4 (Case III)

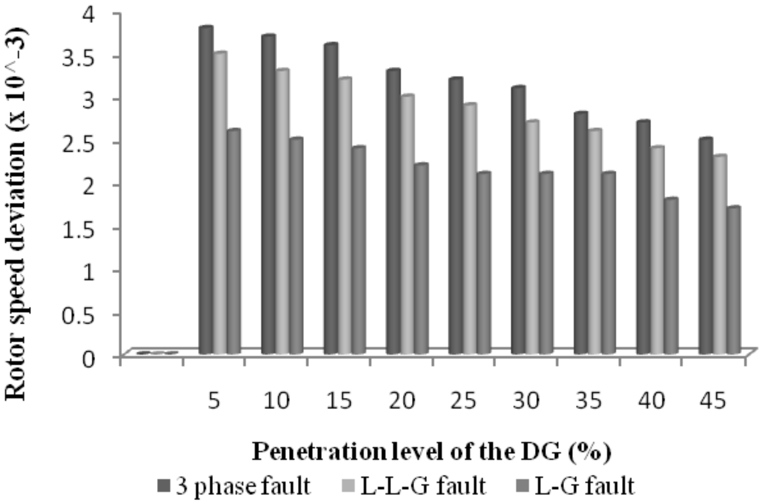


Figure 6.24 Rotor speed deviation for different faults at bus 5 (Case III)

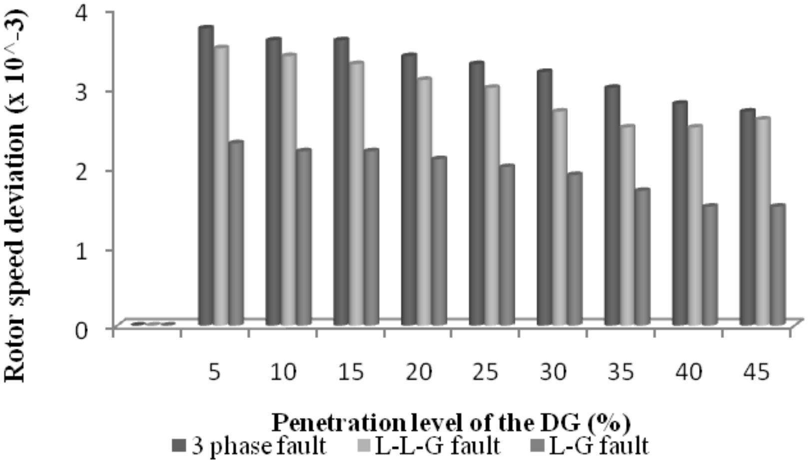


Figure 6.25 Rotor speed deviation for different faults at bus 8 (Case III)

Oscillation duration

Figure 6.26 shows the comparison of the oscillation duration for different types and locations of the faults when a fault is at bus 8. The oscillation durations for the remaining two locations of faults are given in Table 6.6.

The oscillation duration in this case is more when compared to the previous two cases.

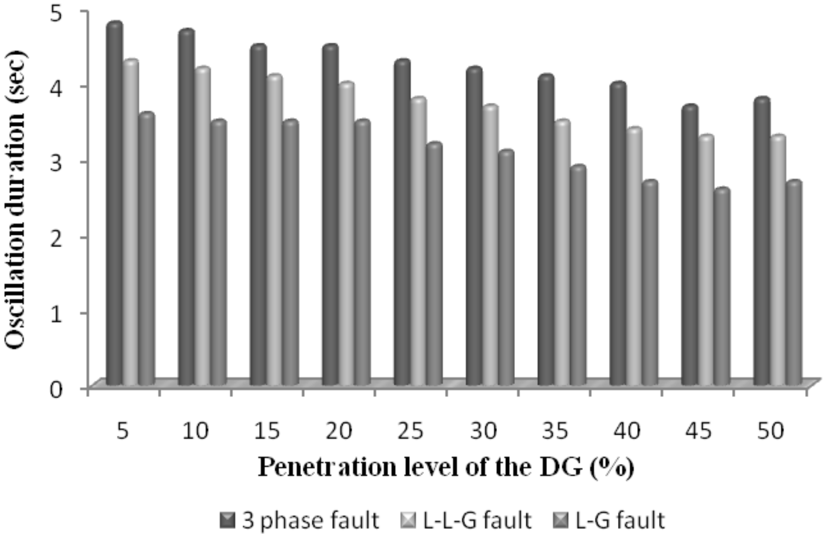


Figure 6.26 Oscillation duration for different faults at bus 4 (Case III)

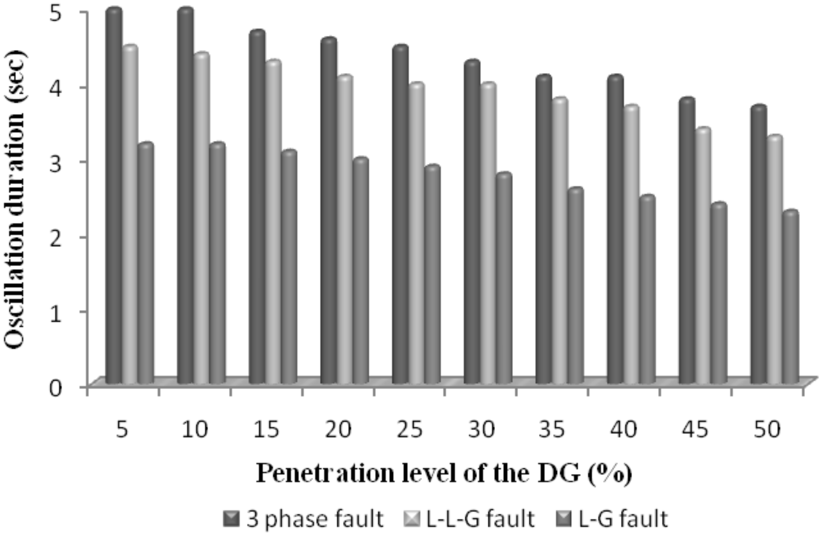


Figure 6.27 Oscillation duration for different faults at bus 5 (Case III)

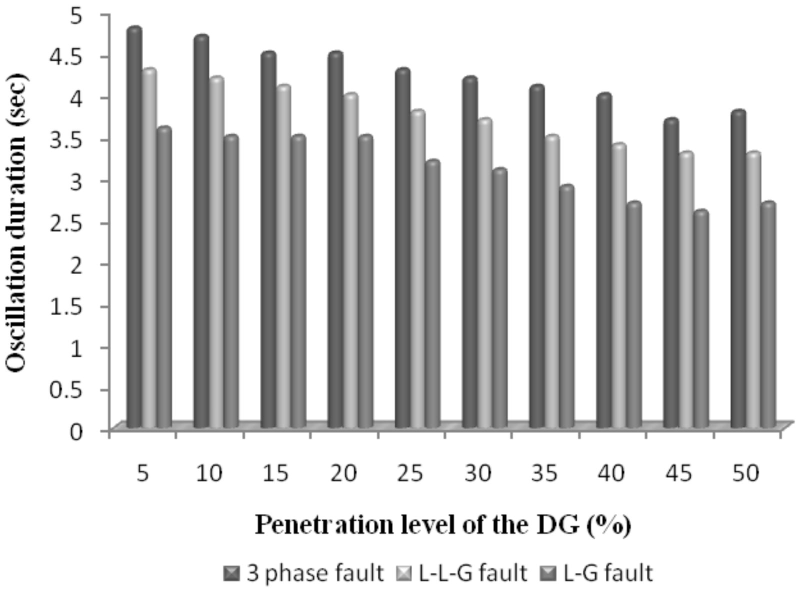


Figure 6.28 Oscillation duration for different faults at bus 8 (Case III)

6.3 Summary

In this chapter the results of the simulation with DG's were presented. Three cases of different load and generation conditions were analyzed. The transient stability of the system was analyzed for the three cases based on the four indicators. It was seen that in all the cases the transient stability of the system was improved when the penetration levels of the DG's were increased from 5% to 50%. But when we compare the three cases, the transient stability had no significant improvement in the case where equal loads were supplied by unequal amounts of power from the DG's.

6.4 References

[1] T. Quoc, L.L Thanh, C. Andrieu, N Hadjsaid, C Kieny, J. C Sabonnadiere, K Le, O Devaux and O Chilard, “Stability analysis for distributed networks with distributed generation”, *Proceedings of the IEEE Transmission and Distribution Conference and Exhibition, May 2006.*

[2] A.K Aarthi, A.K Srivastava and N.N Schulz, “Impact of biomass based distributed generation and energy storage devices on the grid”, *Proceedings of the Power system conference, March 2008.*

CHAPTER VII

SIMULATION RESULTS FOR TRANSIENT ANALYSIS WITH DISTRIBUTED GENERATORS AND ENERGY STORAGE DEVICES

7.1 Introduction

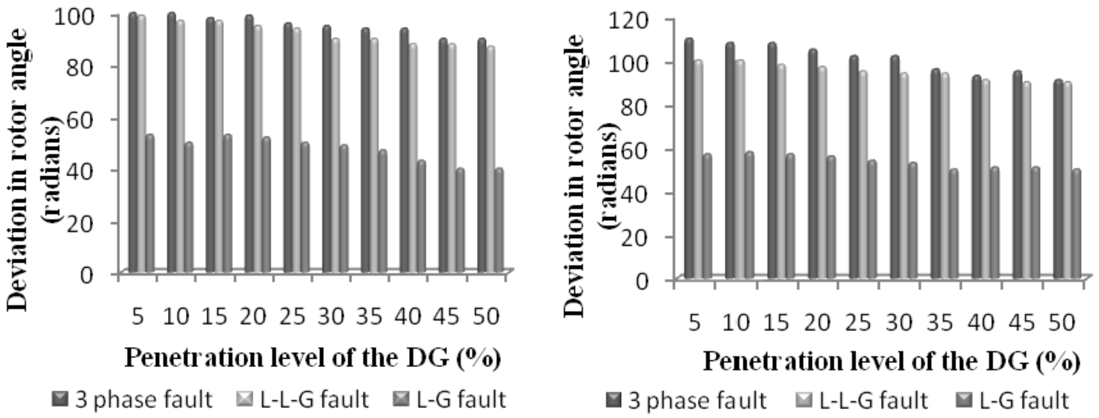
In the previous chapter the results of the transient stability analysis without any energy storage devices were presented. After that analysis, the energy storage devices are connected to the test system by means of power electronic converters and the transient stability is again analyzed with first the battery and then the ultracapacitors. This chapter presents the results of the analysis with the battery and ultracapacitors connected. All the three cases with different generation and load conditions that were considered in the previous chapter are considered in this chapter also.

7.2 Transient stability analysis with energy storage devices

7.2.1 Case I - Equal generation and equal load conditions

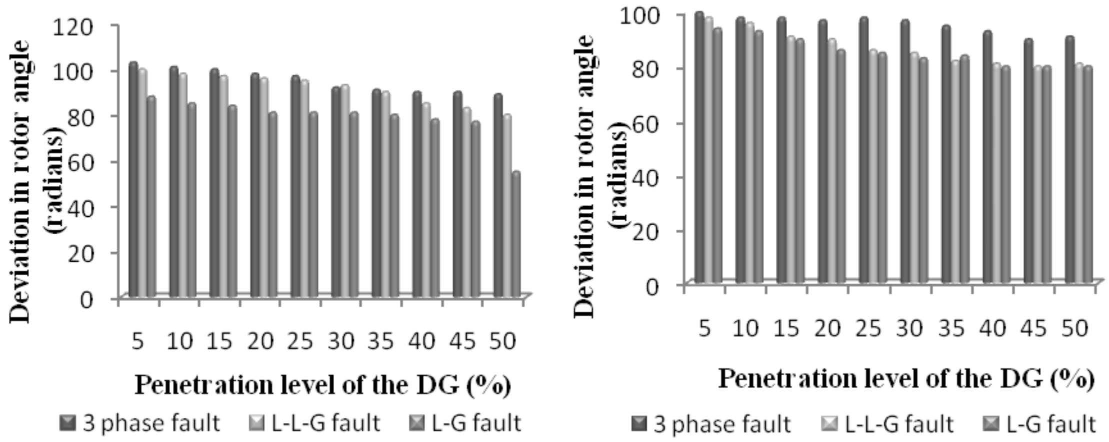
Rotor Angle

The rotor angle analysis is similar to the earlier study without energy storage devices.



(a) (b)

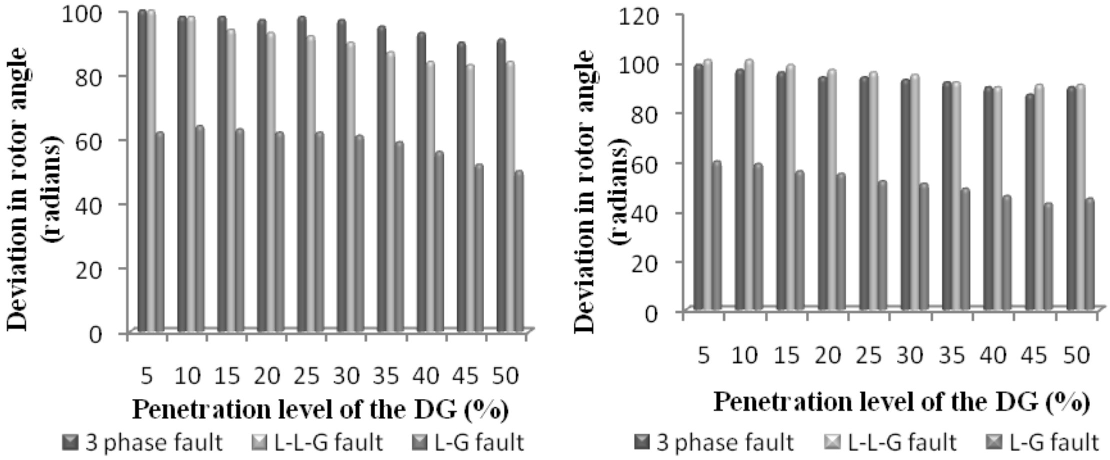
Figure 7.1 Deviation in the rotor angle with (a) battery and (b) ultracapacitor for faults at bus 4 (Case I)



(a) (b)

Figure 7.2 Deviation in the rotor angle with (a) battery and (b) ultracapacitor for faults at bus 5 (Case I)

The rotor angle deviation for faults at bus 4, 5 and 8 with battery and ultracapacitor are shown in figure 7.1, 7.2 and 7.3



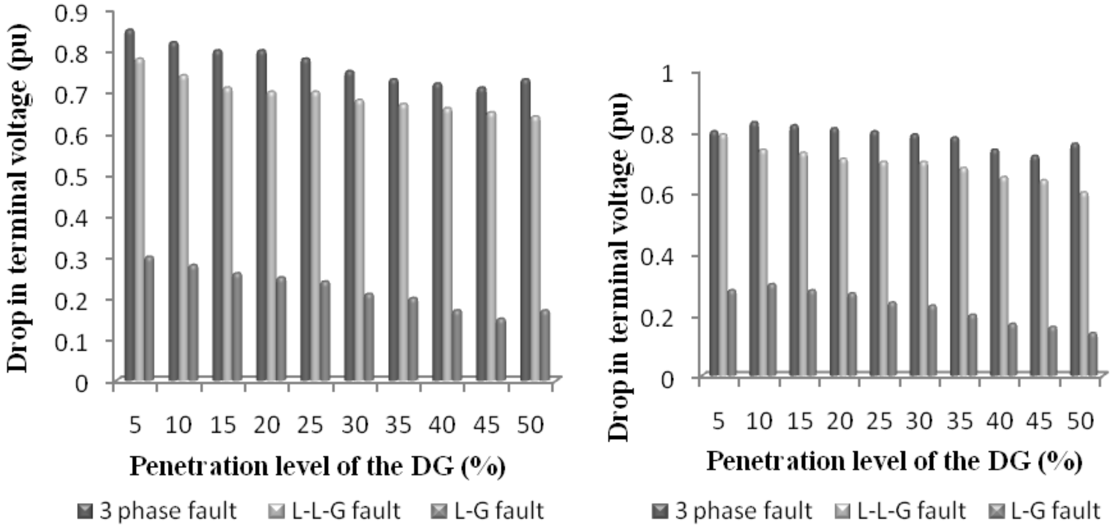
(a) (b)

Figure 7.3 Deviation in the rotor angle with (a) battery and (b) ultracapacitor for faults at bus 8 (Case I)

It can be seen in the table above, that the increase in rotor angle for different types of faults and different penetration levels for a system with battery and ultracapacitors. The transient stability of the system with battery is more when compared to the system with ultracapacitors. But in both the cases the stability increases with increase in the size of DG's.

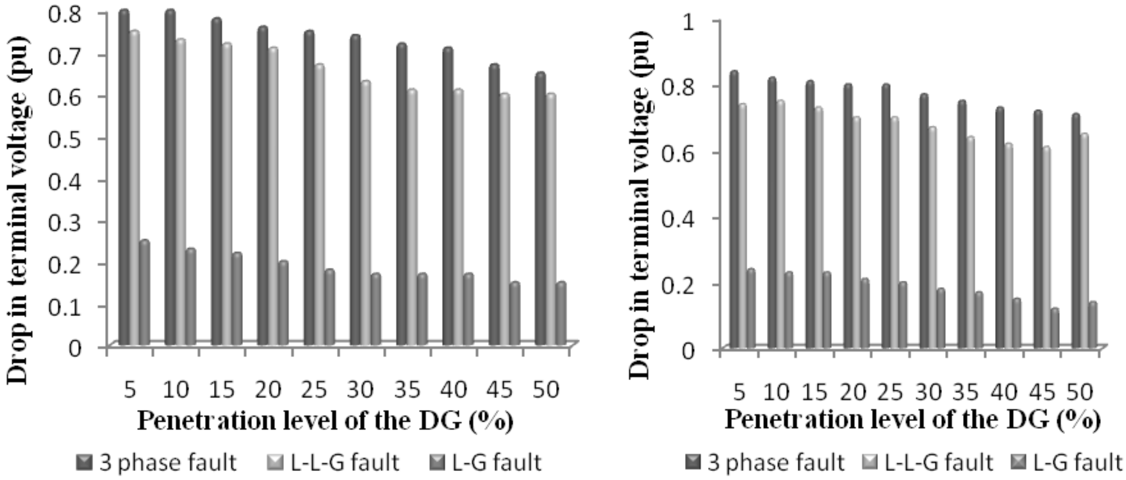
Terminal Voltage

On comparing the results obtained for the terminal voltage with and without the two storage devices it was observed that the addition of the storage devices has decreased the drop in terminal voltage during fault thereby improving the stability.



(a) (b)

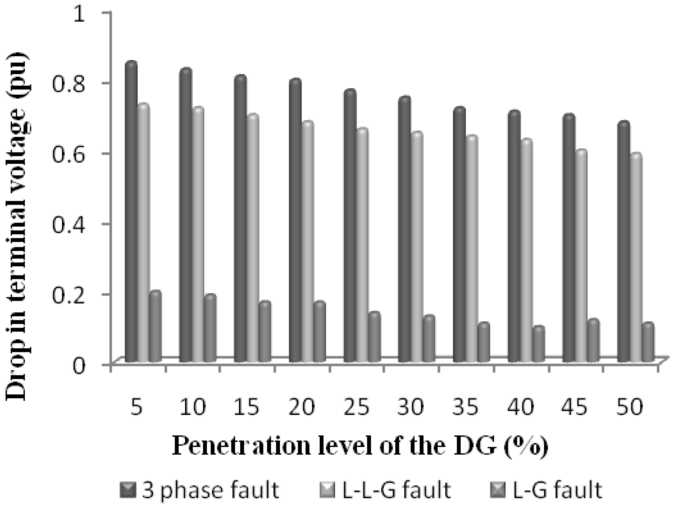
Figure 7.4 Drop in terminal voltage with (a) battery and (b) ultracapacitor for faults at bus 4 (Case I)



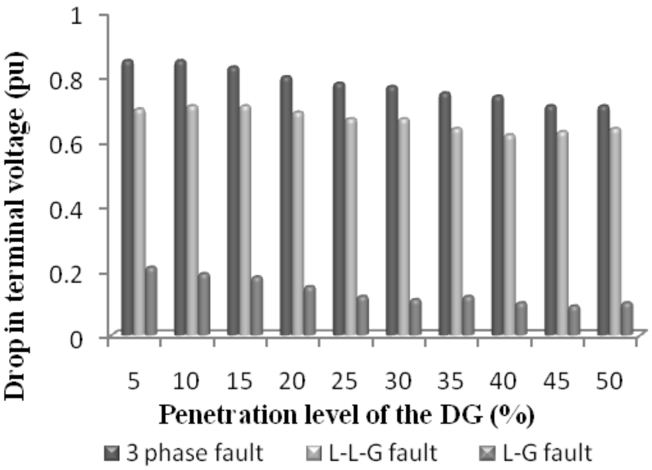
(a) (b)

Figure 7.5 Drop in terminal voltage with (a) battery and (b) ultracapacitor for faults at bus 5 (Case I)

The results that were obtained for the analysis with battery and ultracapacitors for faults at buses 4, 5 and 8 are given in figures 7.4, 7.5 and 7.6, respectively.



(a)



(b)

Figure 7.6 Drop in terminal voltage with (a) battery and (b) ultracapacitor for faults at bus 8 (Case I)

Rotor speed deviation

Table 7.1 below, shows the results obtained for the rotor speed deviation analysis with different types and locations of faults with battery and ultracapacitors. The response was better than that of the analysis without any storage devices.

Table 7.1 Deviation in the rotor speed with battery and ultracapacitor (Case I)

DG Penetration (%)		*Deviation in rotor speed when fault is at bus 4 (x 10^-3)*			*Deviation in rotor speed when fault is at bus 5 (x 10^-3)*			*Deviation in rotor speed when fault is at bus 8 (x 10^-3)*		
		3 Ph	L-G	L-L-G	3 Ph	L-G	L-L-G	3 Ph	L-G	L-L-G
5	Batt	3.2	2.0	3.0	2.0	1.9	2.1	2.0	1.5	1.9
	UC	3.1	2.0	2.9	1.9	1.7	1.9	1.9	1.2	2.0
10	Batt	3.1	2.0	2.9	1.8	1.6	2.0	2.1	1.3	2.1
	UC	3.0	2.1	2.9	1.6	1.6	1.7	1.8	1.2	2.0
15	Batt	3.0	1.9	2.6	1.6	1.5	2.0	1.9	1.2	2.1
	UC	2.8	1.9	2.6	1.4	1.5	1.3	1.5	1.1	1.9
20	Batt	2.8	1.7	2.5	1.5	1.4	1.9	1.6	1.1	2.0
	UC	2.6	1.7	2.3	1.4	1.3	1.2	1.3	1.0	1.8
25	Batt	2.6	1.5	2.2	1.3	1.3	1.7	1.5	1.2	1.9
	UC	2.5	1.6	2.0	1.3	1.2	1.0	1.2	1.09	1.7
30	Batt	2.5	1.4	2.1	1.1	1.2	1.4	1.3	1.0	1.7
	UC	2.3	1.5	1.9	1.2	1.1	1.1	1.0	1.08	1.7
35	Batt	2.3	1.1	2.0	1.0	1.0	1.3	1.2	1.0	1.5
	UC	2.2	1.2	1.7	1.1	1.0	1.09	1.0	1.08	1.3
40	Batt	2.2	1.0	2.0	1.0	1.0	1.1	1.0	1.08	1.4
	UC	2.0	1.0	1.5	1.0	1.1	1.08	1.1	1.06	1.1
45	Batt	2.2	1.0	1.8	1.0	1.09	1.0	1.07	1.08	1.3
	UC	2.0	1.09	1.4	1.0	1.1	1.08	1.08	1.05	1.0

Table 7.1 (continued)

50	Batt	2.3	1.0	1.9	1.1	1.08	1.0	1.08	1.09	1.1
	UC	1.8	1.08	1.5	1.0	1.3	1.08	1.08	1.09	1.3

Oscillation duration

In this case also the addition of storage devices to the system was found to improve the stability of the system compared to the case without energy storage devices.

Table 7.2 Oscillation duration with battery and ultracapacitor (Case I)

DG Penetration (%)		*Oscillation duration when fault is at bus 4 (sec)*			*Oscillation duration when fault is at bus 5 (sec)*			*Oscillation duration when fault is at bus 8 (sec)*		
		3 Ph	L-G	L-L-G	3 Ph	L-G	L-L-G	3 Ph	L-G	L-L-G
5	Batt	3.0	2.2	3	2.9	2.0	3.0	2.7	2.0	2.5
	UC	2.9	2.3	2.9	3.1	2.5	3.3	2.5	2.3	3.0
10	Batt	2.9	2.1	2.7	2.7	1.9	2.9	2.7	2.0	2.4
	UC	2.8	2.2	2.6	3.0	2.4	3.3	2.5	2.3	2.9
15	Batt	2.9	2.0	2.5	2.6	1.7	2.7	2.3	1.9	2.2
	UC	2.7	2.2	2.4	2.9	2.2	3.1	2.1	2.1	2.7
20	Batt	2.8	1.8	2.4	2.5	1.6	2.6	2.2	1.7	2.1
	UC	2.5	2.1	2.3	2.7	2.2	2.7	2.0	2.0	2.5

Table 7.2 (continued)

25	Batt	2.8	1.8	2.3	2.5	1.6	2.6	2.1	1.6	2.0
	UC	2.4	2.0	2.2	2.5	2.1	2.7	1.8	1.9	2.3
30	Batt	2.6	1.6	2.1	2.5	1.4	2.3	2.0	1.5	2.0
	UC	2.2	1.9	2.1	2.2	2.0	2.6	1.7	1.8	2.2
35	Batt	2.4	1.5	2.0	2.2	1.3	2.2	1.9	1.3	1.8
	UC	2.2	1.9	2.2	2.1	2.0	2.5	1.6	1.5	2.1
40	Batt	2.1	1.4	1.8	2.0	1.1	2.0	1.8	1.2	1.7
	UC	2.0	1.5	1.9	1.8	1.8	2.3	1.3	1.4	2.0
45	Batt	2.3	1.3	1.5	2.0	1.1	1.9	1.8	1.0	1.5
	UC	2.0	1.3	1.7	1.7	1.7	2.2	1.1	1.2	1.8
50	Batt	2.2	1.5	1.4	1.9	1.0	1.9	1.9	1.08	1.3
	UC	2.2	1.4	1.6	1.9	1.8	2.0	1.2	1.1	1.9

7.2.2 Case II – Equal generation and unequal load conditions

Similar to the previous case in this case also the transient stability of the system with both the type of storage devices is found to increase as the size of the distributed generators increases. The response of the different indicators are tabulated as before and presented below.

Rotor Angle

The deviation in rotor angle with both battery and ultracapacitors when different types of faults are applied to bus 4 are presented in table 7.3 below.

Table 7.3 Rotor angle deviation with battery and ultracapacitor (Case II)

DG Penetration (%)		*Deviation in rotor angle when fault is at bus 4*		
		3 Ph	L-G	L-L-G
5	Batt	94	46	90
	UC	103	50	97
10	Batt	93	45	88
	UC	103	49	96
15	Batt	92	43	88
	UC	102	49	95
20	Batt	91	42	86
	UC	101	47	94
25	Batt	90	41	84
	UC	100	46	94
30	Batt	90	40	83
	UC	97	45	92
35	Batt	88	40	82
	UC	97	44	91

Table 7.3 (continued)

40	Batt	86	38	81
	UC	95	43	91
45	Batt	85	37	81
	UC	94	42	90
50	Batt	84	36	87
	UC	96	43	90

Similar results have been obtained for faults at buses 5 and 8.

Terminal voltage

Table 7.4 Drop in terminal voltage with battery and ultracapacitor (Case II)

DG Penetration (%)		*Drop in terminal voltage when fault is at bus 5*		
		3 Ph	L-G	L-L-G
5	Batt	0.6	0.2	0.7
	UC	0.9	0.2	0.68
10	Batt	0.56	0.2	0.7
	UC	0.88	0.17	0.64
15	Batt	0.55	0.19	0.67
	UC	0.88	0.16	0.65

Table 7.4 (continued)

20	Batt	0.52	0.18	0.65
	UC	0.87	0.14	0.64
25	Batt	0.50	0.17	0.64
	UC	0.85	0.13	0.62
30	Batt	0.49	0.16	0.63
	UC	0.84	0.11	0.61
35	Batt	0.48	0.15	0.63
	UC	0.82	0.11	0.61
40	Batt	0.47	0.14	0.61
	UC	0.81	0.10	0.60
45	Batt	0.45	0.12	0.60
	UC	0.80	0.08	0.60
50	Batt	0.44	0.12	0.60
	UC	0.82	0.09	0.63

Rotor speed deviation

Table 7.5 below, shows the results obtained for the rotor speed deviation analysis with different types of faults at bus 4 with battery and ultracapacitors. When compared to the case I, the transient stability was found to be poor.

Table 7.5 Deviation in the rotor speed with battery and ultracapacitor (Case II)

DG Penetration (%)		*Deviation in rotor speed when fault is at bus 4 (x 10^-3)*		
		3 Ph	L-G	L-L-G
5	Batt	3.5	2.4	3.4
	UC	3.4	2.3	3.2
10	Batt	3.4	2.3	3.3
	UC	3.4	2.2	3.2
15	Batt	3.2	2.3	3.2
	UC	3.2	2.0	3.0
20	Batt	3.0	2.2	3.2
	UC	3.1	1.9	2.9
25	Batt	2.9	2.1	3.0
	UC	3.0	1.7	2.8
30	Batt	2.9	2.0	2.9
	UC	2.9	1.7	2.7
35	Batt	2.9	1.9	2.8
	UC	2.8	1.5	2.5
40	Batt	2.8	1.8	2.7
	UC	2.5	1.5	2.3
45	Batt	2.8	1.7	2.6
	UC	2.5	1.4	2.2

Table 7.5 (continued)

50	Batt	2.9	1.8	2.4
	UC	1.8	0.08	1.5

Oscillation duration

In this case also the addition of the battery or ultracapacitor to the system was found to improve the stability of the system compared to the case without energy storage devices.

7.2.3 Case III – Unequal generation and equal load conditions

The stability of the system with all three types and locations of the fault and with the two storage devices in Case III was found to be better compared to the case without energy storage devices. But when compared to the other two cases with storage devices, the stability of the system in this case was found to be the least.

7.3 Analysis of the results obtained with and without energy storage devices

This section explains the effects of different conditions on the transient stability.

Effect of fault types

The type of fault is of significant importance when analyzing the transient stability of the system. This can be seen from Figure 7.7 below. The figure shows the comparison of the three types of faults on the rotor speed deviation of the system with and without energy storage devices and with 30% penetration level of the DG and fault at bus 4.

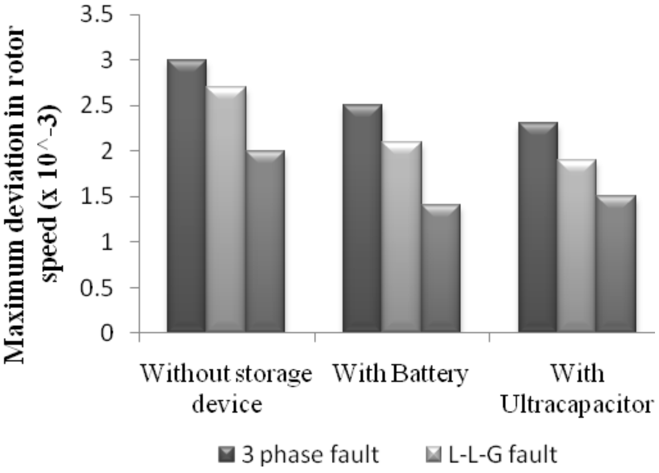


Figure 7.7 Comparison of impacts of different types of faults at bus 4 (Case I)

It can be seen from the figure that a three-phase fault has a greater impact on the transient stability of the system when compared to the other two types of faults. In the example shown above only one indicator, location of fault and penetration level was considered. But from the results presented earlier sections and chapter this trend can be observed in most of the cases. It can be concluded from the analysis that the transient stability is better for a less severe fault as compared to a more severe fault.

Impacts of the fault locations

Similar to the type of fault, the location of a fault must also be considered when analyzing the transient stability of a system. A comparison of the impact of a three-phase fault at different locations on the rotor speed deviation is given in Figure 7.8.

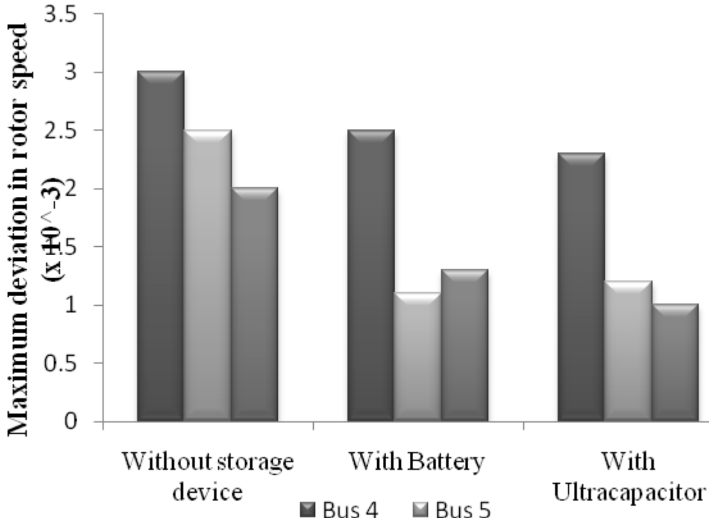


Figure 7.8 Comparison of impacts of different locations of a three-phase fault (Case I)

The comparison presented above is an example of the observed results. In most of the cases, it was seen that the deviation in rotor speed was less when the fault was at bus 8 or 5 whereas it was more when the fault was at bus 4. In certain cases the stability is better for fault at bus 5 and in other cases at bus 8. On an average the transient stability is better when a fault is at bus 8 compared to the other two locations. On analyzing the behavior of transient stability for faults at different locations it can be seen that the distance of the fault from the main source is one of the factors that impacts the stability. When the distance between the main source and the fault is more (bus 8), the transient stability is better when compared to a fault at a smaller distance (bus 4).

Effect of different generation and load conditions

Figure 7.9 shows the comparison between different cases when a three-phase fault is applied at bus 4 with 30% penetration level of the DG.

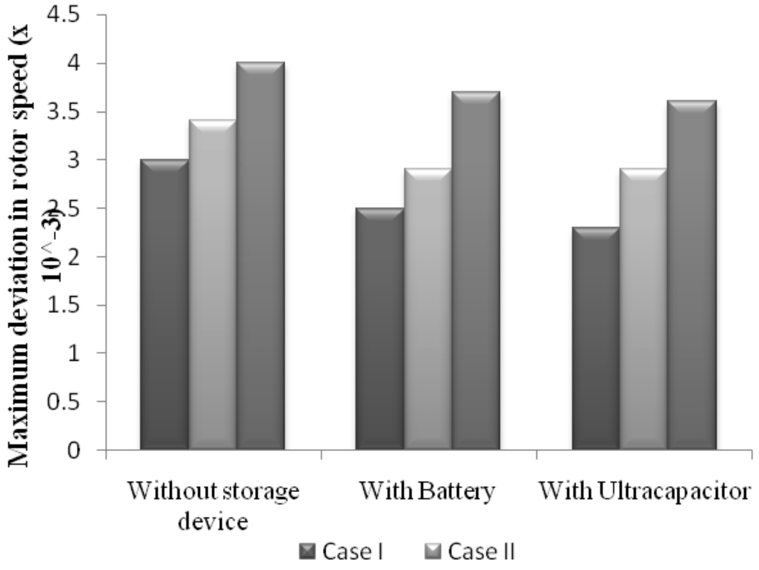


Figure 7.9 Comparison of impacts of different load and generation conditions

Comparing the three different cases that we have considered, it was found that the transient stability was better for equal load and generation conditions (Case I) than cases II and III. Figure 7.9 is an example of one fault at bus 4 with equal and unequal load and generation conditions. Better stability in case I was observed in most of the results with different penetrations, fault types and locations. In a few of the results, better stability might have been observed for the other two cases but on an average, stability was better with equal load and generation conditions.

Impacts of storage devices

In Figures 7.7, 7.8 and 7.9, in addition to the impacts of the factors that were considered, the addition of storage devices also impacted on the overall transient stability. Figure 7.10 shows the comparison of rotor speed deviation with a three-phase fault at bus 4 for different penetration levels of the DG both with and without energy storage devices.

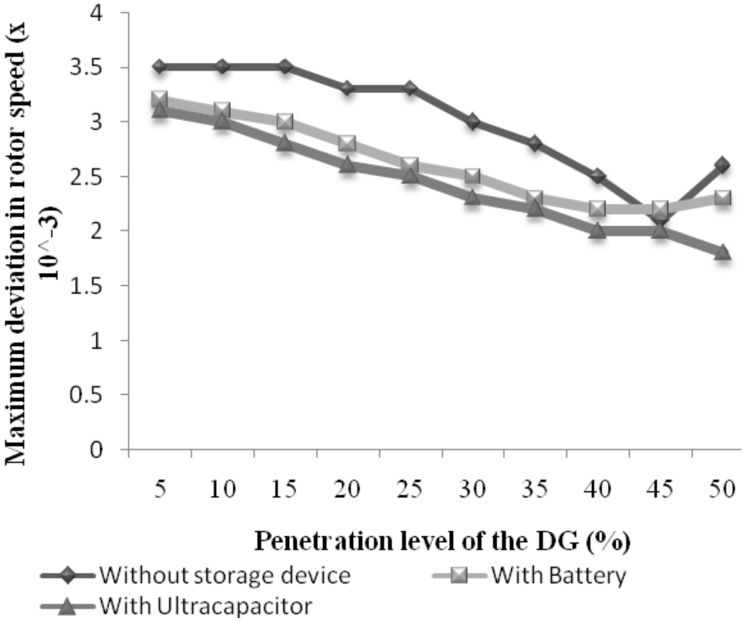


Figure 7.10 Comparison of impacts of storage devices on rotor speed deviation

From the comparison it can be seen that the addition of storage devices decreased the deviation in rotor speed. Also, between the two storage devices, the deviation was more for a battery when compared to an ultracapacitor. Considering this case alone we might come to a conclusion that ultracapacitors provide better transient stability than battery.

Figure 7.11 shows the comparison of oscillation duration for a three phase fault at bus 4 with equal load and unequal generation condition (case II). From this comparison it can be seen that though the addition of storage device improves the transient stability, the performance was better with a battery compared to an ultracapacitor. This is in contrast to the results of the previous comparison.

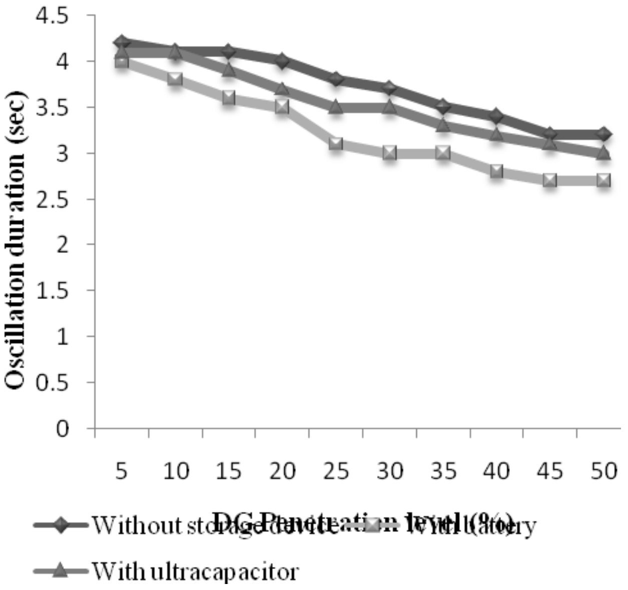


Figure 7.11 Comparison of impacts of storage devices on oscillation duration

In certain other cases it was observed that the performance with battery and ultracapacitor was almost the same. Though it is clearly seen from all the cases that the addition of a storage device improves the stability for sure, these tests were not conclusive on whether a battery or an ultracapacitor provide better stability. Additional studies are needed to determine this.

The interface that has been used to connect the storage devices to the system has a significant impact on the transient stability. Therefore it is necessary to optimize the interface related to the type of storage in order to properly access the impacts of the storage devices on the transient stability.

From the graphs presented in this section, it can be seen that in certain cases, the transient stability increases up to a threshold value after which it starts decreasing. This threshold value is the ideal value up to which the DG penetration can be increased and it depends upon the type and size of the system. For our system the threshold value lies between 45% – 50% of DG.

7.4 Summary

In this chapter the procedure and the results of transient stability study with distributed generators and energy storage devices were presented. The stability of the test system was analyzed under different conditions of generation and load as in the previous chapter. From the results it was seen that the addition of energy storage devices improves the transient stability of the system.

CHAPTER VIII

SIMULATION PROCEDURE AND RESULTS FOR ECONOMIC ANALYSIS

8.1 Introduction

This chapter deals with the economic analysis of distributed generators and storage devices. Three different DG technologies, diesel, wind and biomass, and two storage devices, battery and ultracapacitor are used in the analysis. Each of the DG is used with each of the storage device and the cost of each combination is analyzed. Description of all the components used, along with their costs are explained here. The results obtained from the simulations are discussed and compared.

Most of the previous work related to the economic analysis of DG's had used HOMER to obtain the optimal combination of the DG's and battery. But in our study the purpose of using HOMER is to analyze the effect of the two energy storage devices on the total cost of the system. Therefore in this study we have a fixed size and number of DG's and storage devices.

It also has to be mentioned that for the analysis with ultracapacitors, the battery data is replaced by that of ultracapacitors due to lack of a built-in model in HOMER.

8.2 Description of the system in HOMER

The main components of the system that was built in HOMER are the DG's, electric grid, storage device, converter and the loads. For each simulation, the costs ofeach of the DG and the storage devices are changed based on their type. All the costs involved in the study are obtained from references [3, 4 and 5]. Each of the components that are used in the study is described in this section.

8.2.1 Distributed generator

From the technical analysis of the system in chapter 5, it was seen that the ideal penetration level of the DG is between 45 – 50%. Therefore the distributed generator is considered to supply about 48% of the power whereas the remaining is supplied from the grid. The costs of the three different DG technologies that are used in this study are explained here.

- ☐ Diesel generator - The capital cost of the diesel generator is typically between \$250 and \$500 per kW and the replacement cost is between \$150 and \$300 per kW. Cost of diesel is taken to be \$ 0.8 per liter. The operation and maintenance cost of the generator is \$ 0.001 per kW [3]. The cost decreases with increasing capacity of the generators. Since the capacity of the DG is quite large in our case, costs involved are taken on the lower scale.
- ☐ Wind turbines – The capital cost of the wind turbine are higher than that of the diesel generators. It generally ranges between \$900 and \$1000 per kW [8]. The replacement cost is about 15 – 20% of the original cost and the O&M cost is

about 3% of the original cost [9]. Since in this case too, the cost decreases with increase in capacity, we consider the costs in the lower scale.

- ☐ Biomass generators – The capital cost of the biomass-powered generator is about \$1725 per kW [12]. This includes the cost of the gasifier, generator and transportation cost. In order to calculate the fuel cost, the cost of biomass resources in \$/ton is required by HOMER. Though it depends upon the type of resource, we consider a general cost of \$ 30 per ton [10, 11].

8.2.2 Electric Grid

The system is a grid-connected system and therefore the remaining load, which is left unmet by the DG's, is supplied by the grid. Though the system is connected to the grid, excess power that is produced is not fed back to the grid. The cost of buying power from the grid is selected to be 0.01 \$/kW based on reference [3].

8.2.3 Battery

Since there is no model of lithium ion battery in HOMER, a vanadium redox battery model is selected with the size, cost and other input values corresponding to the lithium ion battery. The capital and replacement costs of a lithium ion battery are \$200 and \$175 per kW, respectively. The replacement frequency of the battery is 10 years considering an efficiency of 85%. The O&M cost of the Li-ion battery is \$25/ kW-yr [4].

8.2.4 Ultracapacitor

As already mentioned in Chapter 3, ultracapacitors are ideal for short-term energy storage. Today there are no bulk units of ultracapacitors in use and also due to factors such as limited production and new technology and the cost of the ultracapacitors are very high. The capital cost of ultracapacitors is about $30,000 per kWh and in case of mass production it is $25,000 per kWh. There is no replacement cost involved for the ultracapacitors. The O&M cost is about $5 /kW-yr [4].

8.2.5 Converter

A bidirectional power converter is used to convert the power. The converter acts as a rectifier when power is stored in the battery and acts as an inverter when power is delivered from the battery. The cost of the power conversion system (PCS) depends on the period of power storage and in turn depends on the type of technology. Similar to all the other components, the cost of the power conditioning devices also drops with increasing capacity. The cost of a PCS for a Li-ion battery system is $200 per kW and for that of the ultracapacitors is $300 per kW [4].

8.3 Simulation procedure

For the simulation three different cases are considered. Each of the cases include three different subsystems which are as listed below:

1. Diesel generator system
    - Without storage devices
    - Diesel-battery system

    - Diesel ultracapacitor system
2. Biomass generator system
    - Without storage devices
    - Biomass-battery system
    - Biomass-ultracapacitor system
3. Wind turbine system
    - Without storage devices
    - Wind-battery system
    - Wind-ultracapacitor system

In the three cases without energy storage devices, the DG is considered to supply approximately 48% to 49% of the load and the remaining is fed from the grid. In this case the total load at each bus is 13MW and so the DG supplies 6.24MW and the grid supplies 6.76MW of power. The capital, replacement and O&M costs of the DG are calculated for this capacity. In all the cases, which include energy storage devices, 10% of the DG power is considered to be supplied by the storage devices. Therefore, the DG supplies 5.616 MW, battery supplies 624 kW and the grid supplies the remaining 6.76 MW of power to the load.

The net present cost of the system for all the cases is calculated based on the HOMER simulation. This cost includes the capital cost, replacement cost, fuel costs and all other costs that are involved for the entire period of the project.

The results obtained from all the three simulations are discussed in the following section.

8.4 Simulation results

Since in our case we have not considered different sizes and quantities of DG's and storage devices, there is only one solution reported by HOMER in all the cases.

8.4.1 Case I – Diesel generator system

1. Without energy storage device

The diesel generator system without any energy storage device is shown in figure 8.1. This case consists of only the diesel generator and the grid supplying the load.

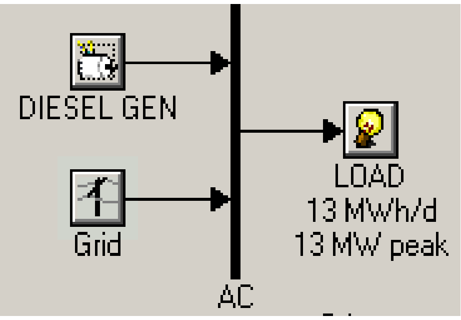
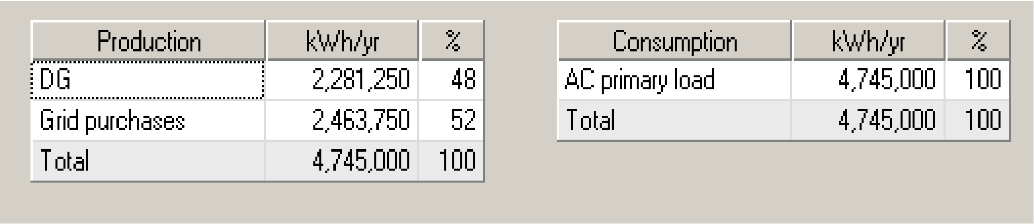


Figure 8.1 Diesel system without storage device

The total production and consumption of electricity is as indicated in table 8.1.

Table 8.1 Total production and consumption of electricity of the diesel generator system



Production	kWh/yr	%
DG	2,281,250	48
Grid purchases	2,463,750	52
Total	4,745,000	100

Consumption	kWh/yr	%
AC primary load	4,745,000	100
Total	4,745,000	100

Table 8.1 shows the average production and consumption of the system. As already mentioned the DG delivers 48% and the grid delivers 52%. The Net Present Cost (NPC) of the system without any storage device was found from the simulation to be $6,903,679.

2. Diesel- battery system

The system consists of the battery in addition to the diesel generator and grid. Table 8.2 gives a detailed summary of the amount of total load and the percentage of power generated of the DG and the grid. It can be seen that total production by the DG and the grid is less than that of the required load. This load that is unmet by the generators is supplied by the battery.

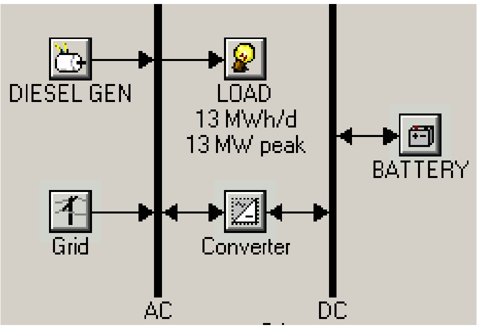
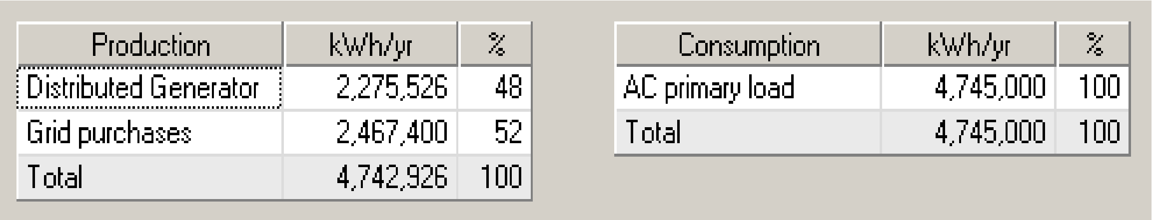


Figure 8.2 Diesel-battery system

Table 8.2 Total production and consumption of electricity of the diesel-battery system



Production	kWh/yr	%
Distributed Generator	2,275,526	48
Grid purchases	2,467,400	52
Total	4,742,926	100

Consumption	kWh/yr	%
AC primary load	4,745,000	100
Total	4,745,000	100

Finally, the total cost of the system with battery is found from the analysis to be $4,970,905.

3. Diesel – ultracapacitor system

The cost of battery is replaced by the cost of ultracapacitors with the size remaining the same as that of battery. Therefore except for the total cost, all the other data remain the same as in the battery simulation. The net present cost of the diesel-ultracapacitor system is found from the simulation to be $5,152,033.

8.4.2 Case II - Wind turbine system

1. Without energy storage system

The diesel generator, in the previous case, is replaced by a wind turbine, as shown in figure 8.3. The net present cost of this system, without any storage device, is calculated to be $6,627,833.

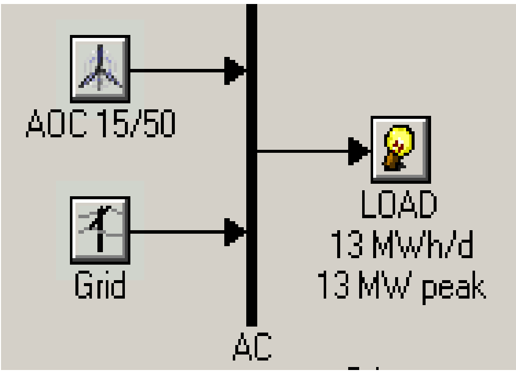


Figure 8.3 Wind system without storage device

2. Wind-battery system

Figure 8.4 shows the wind turbine system with a battery. The Net Present Cost of the wind system with battery is found from the simulation to be $ 6,946,909.

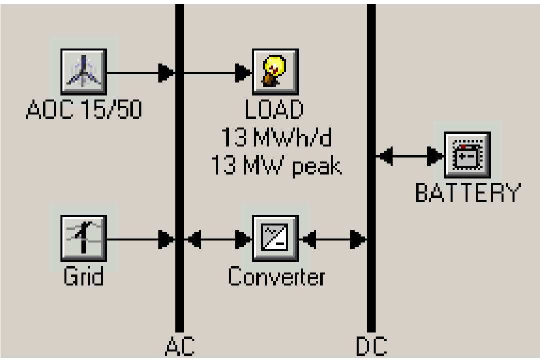


Figure 8.4 Wind-battery system

3. Wind-ultracapacitor system

Similar to the previous case, the data of battery is replaced by the ultracapacitor data. Due to higher cost of ultracapacitor and its converter as compared to the battery, the Net Present Cost is also high in the wind-ultracapacitor system. The NPC is $7,222,969.

8.4.3 Case III - Biomass generator system

1. System without energy storage system

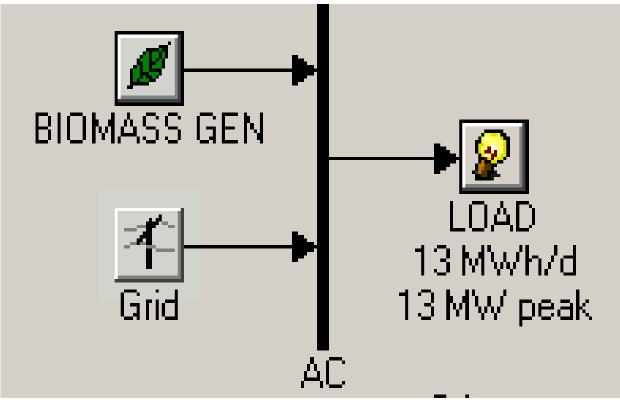


Figure 8.5 Biomass system without storage device

Figure 8.5 shows the biomass generator system without any energy storage devices. The total cost of the system without any energy storage device is calculated to be $14,065,636.

2. Biomass-battery system

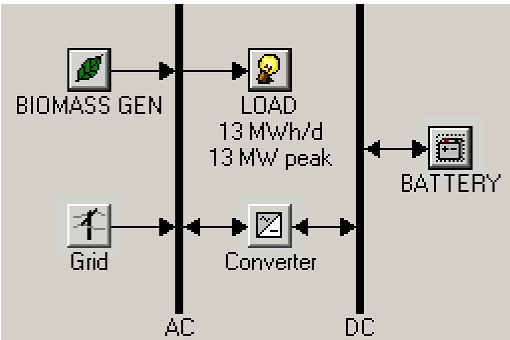


Figure 8.6 Biomass-battery system

The net present cost of the biomass system with a battery storage device is calculated to be $16,163,446.

3. Biomass-ultracapacitor system

The NPC of a biomass system with ultracapacitor is found to be $ 16,413,046.

The total net present costs of the different cases considered are compared and are given in Table 8.3. In case of the diesel generator system, the total cost of the system decreases when an energy storage device is added to it. Between the two types of storage devices, the cost of diesel-battery system was less compared to the diesel ultracapacitor system. This is due to the higher cost of the ultracapacitors. The total cost of the other two systems is not reduced as much as the diesel system.

Table 8.3 Comparison of net present values of different cases

	Without storage device	*Battery*	*Ultracapacitor*
Diesel generator	$6,903,679	$4,970,905	$5,152,033
Wind turbine	$6,627,833	$6,946,909	$7,222,969
Biomass generator	$14,065,636	$15,163,446	$ 15,413,046

8.5 Summary

Economic analysis of different DG technologies and two different storage devices has been done in this chapter. Nine different cases, which include different combinations of DG's and storage devices, were simulated and the net present cost of the combinations is found out. From the results of the economic analysis present above it can be seen that using energy storage devices in the system reduces the net present cost for a diesel generator whereas the cost of wind and biomass system are not as low as the diesel system. The high cost of DG is due to the high cost of the fuel. With reduced costs of ultracapacitors and Li-Ion batteries in the future, the overall cost of the systems can become less. Therefore using energy storage devices to supply a part of the load can actually reduce the overall cost of the system significantly.

8.6 References

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CHAPTER IX

CONCLUSIONS AND FUTURE WORK

9.1 Introduction

This chapter gives a summary of the research work to analyze the technical as well as economic impacts of energy storage devices and distributed generators on the transient stability of the electric grid.

9.2 Research contributions and conclusions

With the increased focus on the distributed generation concept, the necessity to analyze the issues related to it becomes critical. Among the many issues that persist on interconnecting the distributed generators to the grid, the major issue that is being dealt with by a number of researchers is stability. An important component of the distributed generation is the energy storage device. The energy storage devices are critical components especially in systems where renewable energy resources such as wind and solar energy are used. Most of the stability studies do not include the effects that the storage devices can have on the transient stability.

This research work focused on analyzing the transient stability of a system with both energy storage devices and distributed generators connected to it. For the study an 8-

bus test system was built in Simulink. The transient stability of the test system was analyzed based on four stability indicators. The responses of the indicators to different simulation scenarios were observed. The different scenarios include different types and locations of faults and different penetration levels of the distributed generators. This study was done for a system with and without energy storage devices. For this study first order models of a battery and an ultracapacitor have been developed in Simulink. In addition to the technical analysis, this work also deals with the economic analysis to identify if the energy storage devices are economically feasible. For the economic study the net present costs of systems with both the energy storage devices are analyzed separately.

The results of the analysis suggest that using energy storage devices in the system along with distributed generators can improve the transient stability of the system considerably. The impact on transient stability depends on the location and type of disturbances. It was also seen from the results that it is cost effective to use these devices in the system for diesel generators. Ultracapacitors and biomass technologies need to be more cost effective for increased benefits.

9.3 Future work

This study can be further extended to analyze the feasibility of using upcoming techniques for both energy storage and distributed generation. The models of energy storage can be developed further to consider other possible types. These models can be modified to represent more accurate electrochemical storage devices. Detailed generator model will also reflect improvement in the results. Power electronic interface impacts the transient response of the system and can be explored in the future with different architecture of converters. It was seen in the technical analysis that the performance of the interface also impacts the accuracy of the results obtained. Therefore optimization of the interface can be included in future analysis. The test study can be performed for bigger test systems in future.