YASAR UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER THESIS

THE FAULT ANALYSIS OF COGENERATION POWER PLANT

Sezai POLAT

Thesis Advisor: Assist. Prof. Hacer ŞEKERCİ

Department of Electrical and Electronics Engineering

Presentation Date: June 2015

Bornova-İZMİR
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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a dissertation for the degree of master of science.

Assist. Prof. Dr. Hacer SEKERCI (Supervisor)

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a dissertation for the degree of master of science.

Assist. Prof. Dr. Erginer UNGAN

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a dissertation for the degree of master of science.

Assist. Prof. Dr. Nurdan YILDIRIM ÖZCAN

Prof. Dr. Behzat GÜRKAN
Director of the Graduate School

ABSTRACT

THE FAULT ANALYSIS OF COGENERATION POWER PLANT

POLAT, Sezai
MSc in Electrical and Electronics Engineering
Thesis Advisor: Assist. Prof. Hacer ŞEKERCİ
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The analysis of the short circuit should be understood very well in order to make correct designs in the power systems such as the safety of the personnel and the equipment, the selection of the safety relays, the circuit breaker selection and the selection of the appropriate conductor section.

In this study, the parameters about the short circuit and the techniques of calculating the short circuit faults in the system and the necessary theoretical knowledge for the short circuit fault to be understood better have been given. The effect on the distributed generation and the grid which is caused by the possible three-phase short circuit fault and the phase-to-phase short circuit fault has been simulated by being modelled in PSS/SINCAL and by using the real network parameters.

The real short circuit fault results measured from the power plant and the grid and the results obtained from PSS/SINCAL have been compared and it has been determined that there is not a significant difference between them. Thus, it has been emphasized that it is correct to simulate before investing in a power system in order to prevent the faults during the designing and working before the application.

Keywords: Fault, Power Systems Analysis, Short Circuit Analysis

ÖZET

KOJENERASYON ENERJİ SANTRALİNDE ARIZA ANALİZİ

POLAT,Sezai
Yüksek Lisans Tezi, Elektrik ve Elektronik Mühendisliği Bölümü
Tez Danışmanı: Yard. Doç. Dr. Hacer ŞEKERCİ
Haziran 2015, 82 sayfa

Güç sistemlerindeki personelin ve ekipmanların güvenliği, koruma rölelerinin seçimi, koruma şalterlerinin seçimi ve iletken kesitinin seçimi gibi elektrik güç sistemlerinde doğru tasarımların yapılması için kısa devre analizinin çok iyi anlaşılmalıdır.

Bu çalışmada kısa devre ile ilgili parametreler ve sistemdeki kısa devre hatalarını hesaplama teknikleri ve kısa devre arızasının daha iyi anlaşılması için gerekli teorik bilgi verilmiştir. Olası üç faz kısa devre hatası ve faz – faz kısa devre hatasının neden olduğu dağıtık üretim tesisi ve şebekedeki etkisi PSS/SINCAL'da modellenerek ve gerçek şebeke parametreleri kullanılarak simüle edilmiştir.

Bir elektrik santralinden ve şebekeden ölçülen gerçek kısa devre arızası sonuçları ve PSS/SINCAL'den elde edilen sonuçlar kıyaslanmış ve aralarında belirgin bir fark olmadığı saptanmıştır. Böylece uygulamadan önceki tasarım ve çalışma süresince hataları önlemek için bir santrale yatırım yapmadan önce simülasyon yapmanın doğru olduğu vurgulanmıştır.

Anahtar sözcükler: Hata, Güç Sistemleri Analizi, Kısa Devre Analizi

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I offer my sincerest gratitude to thank Ahmet ÖZENİR and Okan TUNÇ from Desa Energy for providing the real data regarding the cogeneration power plant.

I would like to thank my wife for her unconditional love and unfailing support.

Sezai POLAT
İzmir, 2015

TEXT OF OATH

I declare and honestly confirm that my study, titled “The Fault Analysis Of Cogeneration Power Plant” and presented as a Master’s Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions, that all sources from which I have benefited are listed in the bibliography, and that I have benefited from these sources by means of making references.

Sezai POLAT

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INDEX OF SYMBOLS AND ABBREVIATIONS

Symbols	**Explanations**
A	Initial value of the DC component
C_{max}	Voltage Factor
f	Frequency
$i_{d.c.}$	Decaying DC component
I_k	Steady state short circuit current
I_k'	Transient short circuit current
I_k''	Initial or subtransient symmetrical short circuit current
i_p	Peak short circuit current
k	The value of the equivalent impedance of the components (X/R) along with a rate
R	Resistance
t	Time
U_n	Nominal Voltage
Z_k	The equivalent short-circuit impedance of the network
X	Inductance

Abbreviations	**Explanations**
AC	Alternating Current
ANSI	American National Standards Institute

INDEX OF SYMBOLS AND ABBREVIATIONS (cont'd)

Abbreviations	**Explanations**
DC	Direct current
DG	Distributed Generation
GT	Gas Turbine
IEC	The International Electrotechnical Commission
PV	Photovoltaic
TEDAŞ	Türkiye Elektrik Dağıtım A.Ş
VDE	Verband der Elektrotechnik, Elektronik und Informationstechnik
XLPE	Cross-linked PolyEthylene

CHAPTER 1

INTRODUCTION

1.1 Background

The electrical power system has an important role in the development of human life. It is known that electricity is one of the main necessities in human habitat. The requirements in life have increased continuously and have been related to the demands. Through the best utilization of maximum energy resources and components to generate electricity, it is possible to satisfy the customer needs. Alternative energy sources such as wind turbines, solar panels, combined cycle power plant and wave power plants have started to play an important role in the global energy system with the raise in power demand (Gakhar 2013).

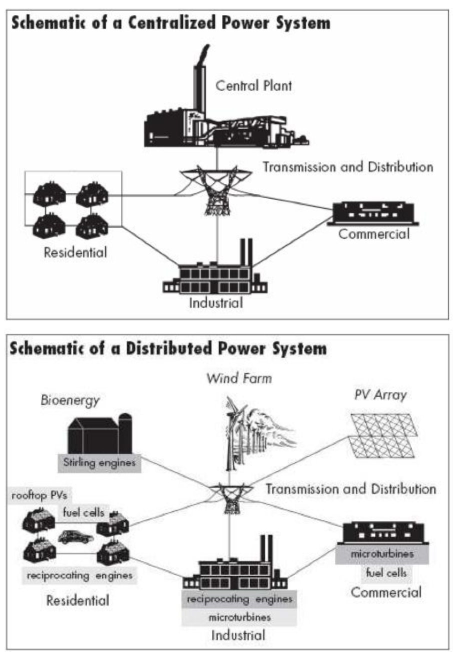


Figure 1.1 Schema of centralized and distributed power system (Wikipedia, 2015)

The integration of alternative energy sources into the power system may potentially cause serious difficulties for the control and protection of large central generators and the distribution system. A correct design, planning, installation and operation of complex distribution system with alternative energy sources should be carried out.

Figure 1.1 shows a generalized view of distributed generation integrated to the main electricity grid.

The electrical transmission and distribution play a great role in transporting energy from the generator to customers. In spite of the capacity of such a complex network, constant disturbances remain in the system which may be dangerous both for the customers and the power electronics equipment in the network (Gers, 2004). For this reason it is recommended that the damage caused by disturbances should be limited and isolated by fast switching protection devices without affecting the rest of the distribution system.

1.2 Scope and Objective

The main objective of this thesis is to study and understand faults and search their effects on power system. In the Thesis, it has been studied the effect of the short circuit type of the fault on the power system and specially focused on the effect of grid on the power system during this type of fault.

The field of the study has five plants, a grid connected the power plant and an electrical distribution system to feed the plants in the industrial zone.

The analysis has been done in a practical way by modeling of whole system in software and making simulations for different cases.

The specific tasks include:

- Making the simulations on the software and modeling of loads, generators, transformers, capacitors, lines etc.
- Creating a few different cases to study and simulating on the software to show the effect of the power system.
- Making the simulations for each case with different operational conditions and showing the fault current and voltage at all buses.

The main objective of the thesis is the impact of the distributed generation on the distribution system during the short circuit conditions and their effect on the power system.

In order to analyses the cases a medium voltage 34,5 kV network is built in PSS/SINCAL software. The simulation will be considered on different types of synchronous machines, transformers, lines and different fault locations in addition to the different fault types.

The results show how different fault types create variations of voltages and currents in all buses and impact the protection system circuit breakers coordination in the distribution system with the integration of distributed generation in the network. They also show what will be the best recommended protection of distribution system in case of integration of distributed generation in the network.

The power flows, bus voltages and increases - decreases of the magnitudes of voltages and currents and transients due to line fault are also examined. These faults are applied at different locations and types and the response of each bus before, after and during the fault is observed.

1.3 Literature Survey

The industrial power system studies primarily consists of the techniques used to size and selection of equipment and predict or improve the performance of an existing or proposed power system under specified conditions. The power system optimization for industrial facilities can be achieved through the combination of several power studies short circuit studies are one of the most important as compare to other fundamental power system studies. Short circuit in a system creates high magnitude currents, which is many times greater than load currents. The consequences of this short circuit study determine fault current in system for various faults (Renuka Kamdar, Mukesh Kumar Kirar, Manoj Kumar, Ganga Agnihotri, 2013).

A study of the Renuka Kamdar , Mukesh Kumar Kirar, Manoj Kumar and Ganga Agnihotri was carried out short circuit analysis of an industrial electrical power distribution system in compliance to IEC 60909. The Simulation and short circuit study of an industrial electrical power distribution system was performed on ETAP software. The short circuit studies were performed by considering different types of faults in system and I_k'', i_p and I_k were determined. The results of short circuit studies were useful in order to determine system configuration, system voltage levels, protection equipments, switchgears, and cables size, transformers, grounding and earthing (Renuka Kamdar, Mukesh Kumar Kirar, Manoj Kumar, Ganga Agnihotri, 2013).

In investigation of Jyotsna Sharma and Akhilesh Dobhale analyses were based on the investigation of the impact of DGs on the efficiency at fault location. The location of DG was a changed and fault power was calculated at fault location. They studied the location of single-phase fault observed and simulated a distribution system containing a DG for three phase fault. They had developed an application in Matlab/Simulink that can obtain the distribution system of 11 kV containing 18 bus lines and then fault power was analyzed at fault location. In order to obtain maximum benefit from the distributed generator, suitable location and sizing had to be determined before its installation. The study showed that the far the DG was from fault location the more isolated it was (Jyotsna Sharma, Akhilesh Dobhal, 2014).

In this research (Adnan Kakilli, 2013), the balanced three phase fault current at a given bus of the system was calculated by using different methods. The objective was to find how much short circuit current flows from the sources to the fault, when a symmetrical three-phase short circuit occurs at any location (buses or lines) in a power system. As an example, an industrial power plan had two generators was analyzed. It was connected to the 138 kV system of the power plant. The Ohmic Method, the Per-Unit Method and the MVA Method were compared. The MVA method was easier than the other methods was obtained. Both the ohmic and the per-unit methods usually end up with small decimals resulting from converting impedances from one voltage level to another one or from converting impedances to the same common base. Therefore, one can make mistakes easily. Especially emphasis on the MVA method and compared other conventional methods for industrial power system short circuit calculations (Adnan Kakilli, 2013)

In study (Ansuman Mohapatra, Basanta Kumar Panigrahi, 2014), complete models of hybrid photovoltaic generation and wind power generation systems were developed under Matlab/Simulink. Then these models were simulated under different fault conditions. This study showed a hybrid system powered by renewable energy sources such as wind and photovoltaic generation system. Two operational modes dictated by the availability of the grid, wind power generation unit and photo voltaic generation unit were identified for operation of the proposed hybrid power system. The hybrid power system behavior was also observed with different types of fault condition. The system behaviors in each fault condition revealed the technical challenges and the additional necessities for operating the proposed wind and photovoltaic source based hybrid system. The control and management protocol outlined in this research was required to be developed along with additional components for stable and autonomous operation of the proposed hybrid system (Ansuman Mohapatra, Basanta Kumar Panigrahi, 2014).

In paper, authors Kadam Sandeep Ratnadeep and YN Bhosale, Shrihari Kulkarni present fault analysis for power distribution system is important for proper selection of protective devices and it is useful for safety of person working in the substation. With the help of fault analysis, it could be calculate fault currents for different types of faults in a substation. They said that Fault analysis was also necessary for determining fault MVA and voltage at the time of fault at fault location. Most commonly occurring fault was single line to earth fault and most dangerous fault is three-phase fault. Fault level analysis of power distribution network was required for selection of protective devices such as relays and circuit breakers. In this study, fault level analysis of 33/11 KV power distribution substation was carried out by using symmetrical component method in Matlab simulation (Kadam Sandeep Ratnadeep, Y.N. Bhosale, Shrihari Kulkarni, 2013).

J. Faig, J. Melendez, S. Herraiz and J. Sánchez were studied the location of single-phase faults in power distribution systems with distributed generation by means of impedance-based methods. These methods were based on the measurement of voltages and currents and in one measurement, point and distributed generation caused errors in the estimated location. They had developed an application in Matlab/Simulink that can obtain the distribution system and then fault power was analyzed at fault location. The research showed the influence of parameters such as the magnitude of distributed generation, the fault impedance and the relative position of the fault location and the distributed generation in the estimated location (J. Faig, J. Melendez, S. Herraiz and J. Sánchez, 2010).

The key subjects defining and classifying fault is given in detail in literature. The primary power system components that have effect on fault analysis are argued in a number of works.

The fault analysis has been done in different studies with also different methods and software is discussed. This thesis have similarities with some studies in that the effect of fault on distributed generation power system have been analyzed for an cogeneration power plant. In addition, this thesis also shows a frequency deviation during the faults.

1.4 Organization of Thesis

Chapter 1; Briefly overview of the purpose of the study

Chapter 2; Introduction of the distribution generation and technologies

Chapter 3; Review of the electricity generation in the power plant

Chapter 4; Definition of the theoretical background and mathematical analysis of the calculations of the fault types

Chapter 5; Presentation of the power plant modeling in the software

Chapter 6; Introduction of the simulations of the different cases on power system simulation software and the analysis of the results obtained by the simulations

Chapter 7; Introduction of the conclusions of the analysis

Chapter 8; Suggestions for the future applications by taking notice of the result

CHAPTER 2

DISTRIBUTED GENERATION

2.1 Distributed Generation

At power networks, the electricity is generated by large-scale power plants and transmitted through the transmission and distribution networks to the end users. This concept is called as “The Centralized Generation”. Distributed generation or decentralized generation is an approach in which small-scale generators installed are implemented on the low-voltage networks by the customers or the utility companies (Jenkins, 2010).

2.2 Distributed Generation Technologies

The distributed generation technologies are divided as traditional and non-traditional. The traditional distributed generation technologies include combustion turbines, diesel engines, micro-turbines and natural gas engines. The others are mostly renewable energy technologies (El-Khattam, 2004).

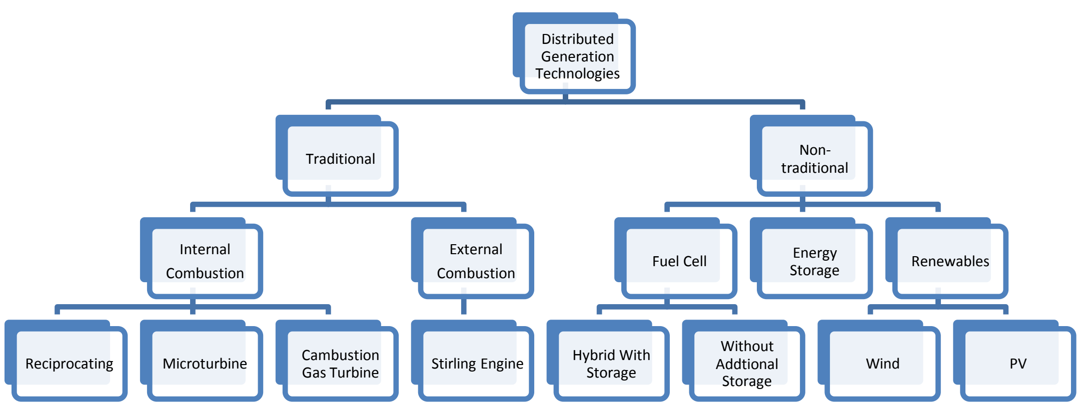


Figure 2.1 Distributed generation technologies (El-Khattam, 2004)

The definitions of some of the distributed generations used most commonly are given below.

2.2.1 Gas turbine power plant

The schematic replacement of a gas turbine power plant is shown in Figure 2.2 the main components of plants are (Jeffrey M. Smith, 1996);

- Compressor
- Regenerator
- Combustion Chamber
- Gas Turbine
- Alternator
- Starting motor

2.2.1.1 Compressor

The compressor in the plant is usually a rotatory type. The air at atmospheric pressure is aspirated by the compressor that has a filter for the dust from the air. The rotatory blades of the compressor push the air between stationary blades to raise its pressure. In this way, the air at high pressure is available at the output of the compressor (Jeffrey M. Smith, 1996).

2.2.1.2 Regenerator

A regenerator is a device that gets heat from the exhaust gases of the turbine. The exhaust is passed through the regenerator before wasting to atmosphere. A regenerator consists of a nest of tubes contained in a shell. The compressed air from the compressor passes through the tubes on its way to the combustion chamber.

In this way, the compressor is heated by the hot exhaust gases.

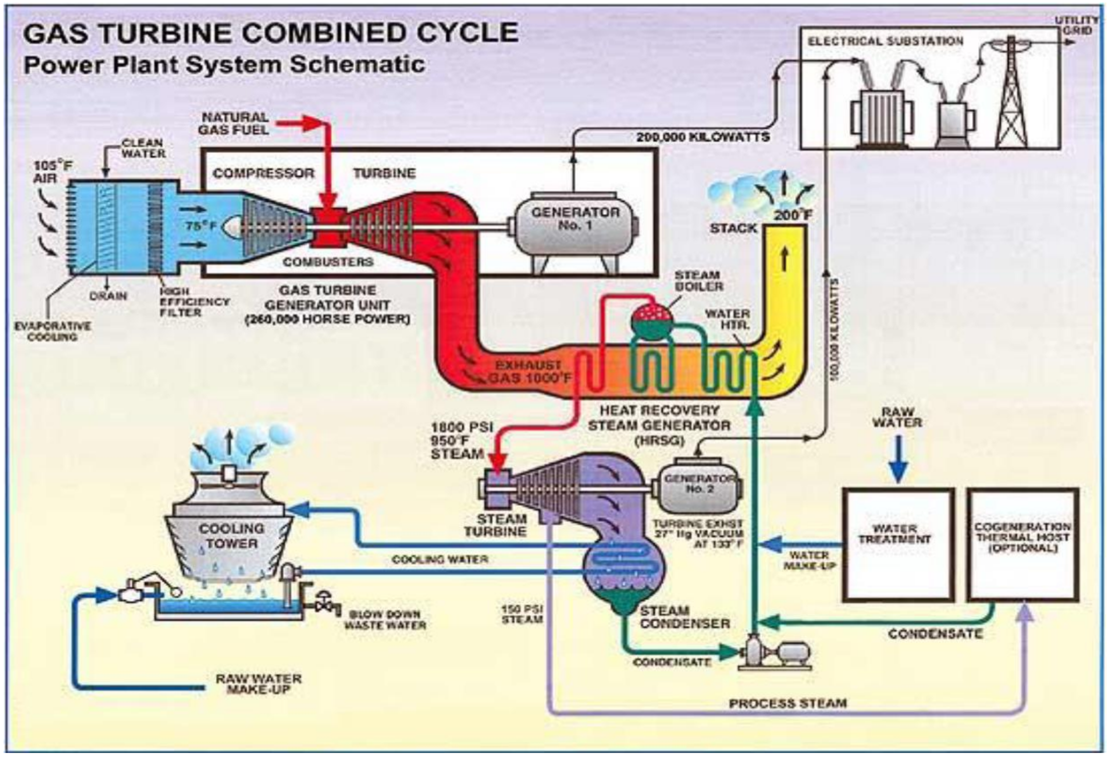


Figure 2.2 Gas turbine power station (IGNOU, 2015)

2.2.1.3 Combustion chamber

The air at high pressure from the compressor is led to the combustion chamber via the regenerator. In the combustion chamber, heat is added to the air by burning oil. The oil is injected through the burner into the chamber at high pressure ensure atomization of oil and its thorough mixing with air (Mehta, 2005). The result is that the chamber attains a very high temperature. The combustion gases are suitably cooled and then delivered to gas turbine.

2.2.1.4 Gas turbine

The products of combustion consisting of a mixture of gases at high temperature and pressure are passed to the gas turbine. These gases in passing over the turbine blades expand and thus do the mechanical work. The temperature of the exhaust gases from the turbine is about 900ºF (482ºC) (Jeffrey M. Smith, 1996).

2.2.1.5 **Alternator**

The gas turbine is coupled into the alternator. The alternator converts the mechanical energy of the turbine into electrical energy. The output of the alternator is given to the bus-bars through transformers, isolators and circuit breakers.

2.2.1.6 **Starting motor**

Before starting the turbine, compressor has to be started. For this purpose, an electric motor is mounted on the same shaft as that of the turbine. The motor is energized by the batteries. Once the unit starts, a part of the mechanical power of the turbine drives the compressor and there is no need of the motor now (Jeffrey M. Smith, 1996).

2.2.2 **Reciprocating engines**

This technology which is still widely used in most of the applications was developed nearly a century ago. The power of engine's range in size changes from 10 kW to 18 MW using diesel, natural gas, or waste gas as their fuel source (Ken Darrow, 2015). The reciprocating engines are used mainly for backup power.

2.2.3 **Micro turbine**

An emerging technology, micro turbines, show low emission level, but they are extremely expensive. The manufactures of micro turbine are willing to compete at the sector of production of generators whose models range from 30 to 200 kW (Gakhar, 2013). This technology is at the step of testing and applications of the micro turbines are not very common yet.

2.2.4 **Photovoltaic**

Photovoltaic generate electricity is a process directly from sunlight which occurs with certain types of materials. The solar energy makes the electrons in this material free and the electrons circulate in an electrical circuit and by means of this, they provide the power for the electrical devices. This technology is used in industrial area and in the other living area. The photovoltaic generate electricity is available for the remote locations without grid connections and in order to provide power to the grid.

2.2.5 Fuel cells

The cost of the fuel cells and their reliability are the main problems for this technology. They are used for the combined heat and the power application. They produce DC power for which an inverter is required to convert it into AC power.

2.2.6 Wind turbine system

The modern wind turbines can provide clean energy as individuals or as wind farms. The wind turbine blades usually are two or three each of which is nearly 140 meters. This system ranges in size from 5 kW to 7500 kW (Jenkins, 2010). The wind turbines are used in remote areas and which are not connected to grid. Today, they are also widely used as connected to grid.

2.2.7 Biomass

The biomass plants are usually of limited size due to the cost of transporting fuel with relatively low energy density. These smaller plants, typically of less than 50–100 MW in capacity, are then connected into the distribution system (Jenkins, 2010). The biomass fuel and feedstock include forestry byproducts, used railroad ties, high-moisture animal waste or liquid effluents produced in ethanol distilleries and food processing plants (Jenkins, 2010). The gasification is an option for well-contained conversion of biomass to power, using the resulting syngas in boilers or an internal combustion engine generator.

2.3 Applications and Advantages

The distributed generation can be applied to improve the reliability and power quality of the electrical system while supporting local utility infrastructure by reducing congestions in transmission and distribution. Some of the fundamental applications of the distributed generations include:

• Base Loading – DG's produce electrical energy continuously while they are connected to the distribution system.

• Islanding – DG generates electrical energy as isolated from the grid.

• Support – DG is used to strengthen systems with high demand variations.

• Load Leveling – Supply peak demand locally to avoid transmission congestion and running more expensive units.

These applications have advantages for the user and the producer. The available technologies supply electrical energy at low cost and good quality. They can also prevent the intermittencies in the electrical system, which cause great losses for the big industrial and commercial users. Some of the DG advantages and disadvantages are (Angelopoulos, 2004);

A. Advantages for the user;

- Increased reliability,
- Increased power quality,
- Reduction in the interruption number,
- Efficient use of energy,
- Lower cost of energy,
- Use of renewable energy,
- Reduction of pollution emissions.

B. Advantages for the producer;

- Reduction in the transmission and distribution losses,
- Increase the capacity system,
- Improve the stability,
- Extended equipment service life,
- Reduce congestion,
- Voltage support,
- Improved small signal stability, due to low constant of inertia,

- Loss of synchronism of a small DG unit has less impact on the local network voltage as oppose to loss of synchronism in a large power plant, which has a higher impact on the voltage, frequency and stability of the network,
- DG reduces post fault voltage oscillation,
- Increased critical clearing times.

C. Disadvantages for both users and producers;

- Increased short circuit current,
- Increased the protection cost,
- Possibility of islanding,
- Possibility of flicker,
- Possibility of over voltage,
- Retrofit costs.

CHAPTER 3

POWER PLANT

3.1 Industrial Power Plants Definition

The industrial power generation has been a widely practice from the beginning of the electric age till now. Because important changes occurred in the power generating industry, such as the economy scale in generation, the demand increase, the price increase and the reliability decrease and so on, most of the industrial plants have shifted away towards generating their own power instead of purchasing electricity from centralized generations.

As a result, industrial plants have invested to generate their own power. The independent power production has several advantages

- Higher energy conversion efficiency resulting in lower energy cost
- Environmental benefits to increase the reliability and economic considerations.

3.2 Design of Industrial Power System

The power system analysis is one of the basic activities that would be required to be performed during the design of the industrial power system. One of the important aspects in the design is planning the protective equipment for the power system. The short circuit analysis of power distribution system is just as basic and important as other fundamental power system studies such as power flow studies to analyze the power requirements of the plant and plan for back-up system, transient stability analysis to determine the effect of the system during disturbances, harmonic analysis to ensure the quality of the power supply, and etc. The short circuit current allows the designer to apply and coordinate protection schemes with proper selections and settings of relays, circuit breakers, fuses, and motor starters.

While planning an electrical system that will be connected to the grid or isolated from the grid, the amount of generating capacity is a rather basic decision made by the designer. Usually, sufficient generation is provided to meet the load requirement, both in the normal situation and under various operation conditions such as large motor starting, load peaking, planned or unplanned generator outages. When an industrial plant is tied to a utility from which it purchases a part of its power needs, with implant generation supplying the rest, the state is more complex and the matter of the system protection is serious (Ramachandran, 2011).

3.3 Electricity Generation and Cogeneration System

The power plant is assumed as an industrial cogeneration system including electrical distribution system to the factories of an industrial zone. Firstly, the heat energy is converted to the mechanical energy and then it is converted to the electrical energy through the turbine shaft and the generator coupled. The converted electrical energy is given to the electricity distribution system at the 34,5 kV voltage level. In this study, electricity production and electrical distribution is carried out with the 34,5 kV voltage level.

In the power plant, there are two turbines each of which is at 6,5 MVA power. While the produced electricity is at 6,3 kV voltage level, it is converted to the 34,5 kV voltage level by the transformers at 6 MVA of power. If it is needed less energy in the plants, the extra electricity, which is produced, is supplied to the grid. In case of the disability of TEDAŞ system, the power plant works as "Island Mode Operation"

CHAPTER 4

SHORT CIRCUIT ANALYSIS

4.1 Overview

The power system studies require the main and necessary steps in designing a new power system or expanding an existing system. Load flow study, transient analysis, motor starting study, harmonic analysis, and short circuit analysis are the different types of analysis a designer does during the planning steps of a power system.

The short-circuit calculations performed within the standard are based on an equivalent impedance representation of the electrical system which is working. When a short circuit occurs, the all considered internal impedance replaces components, and an equivalent voltage source is implemented at the fault node. This voltage source is the only supplying force of the short circuit current and all other sources are calculated as zero (Gers 2004). The considered electrical system in Figure 4.1.

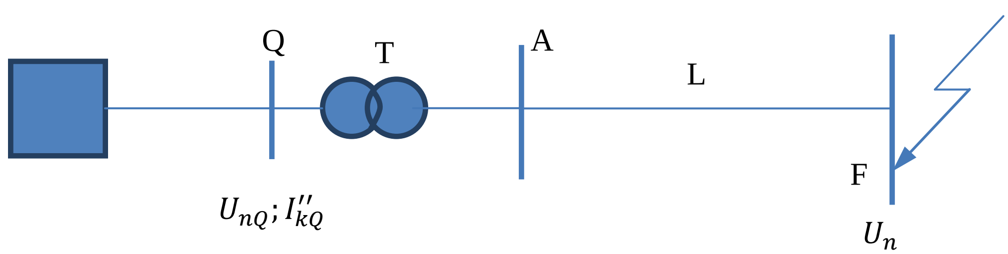


Figure 4.1 Electrical systems (IEC, 2001)

The Equivalent short-circuits impedance of the system electrical system is shown in Figure 4.2.

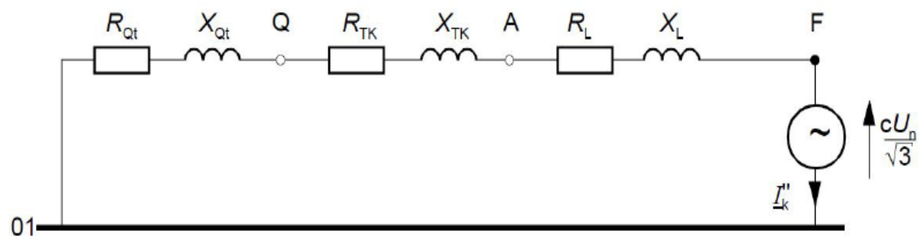


Figure 4.2 Equivalent short-circuit impedance of the system (IEC, 2001)

4.2 Short Circuit Currents

Several methods for the short circuit current calculations can be defined in power system. The short circuit current for a far-from the generator circuit is illustrated in Figure 4.3 (Tleis, 2008). How a fault is far from the generator, it is assumed to have constant AC amplitude, while a fault is near to generator it has a decaying DC component.

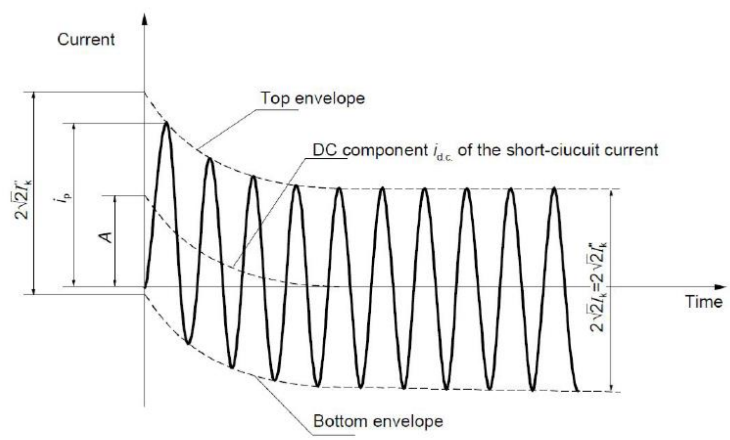


Figure 4.3 Short circuit current far-from-generator (IEC, 2001)

4.2.1 Subtransient short circuit current

The short circuit current for a near-from the generator circuit is illustrated in Figure 4.3 (Tleis, 2008-IEC, 2001).

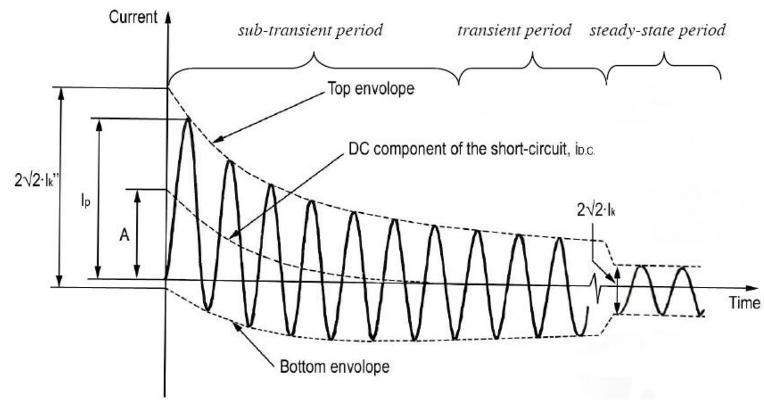


Figure 4.4 Short circuit current near-to-generator (IEC, 2001)

For a three-phase fault, the maximum subtransient short circuit current I_k'' *(1)* can be calculated from

$$I_k'' = \frac{C_{max} U_n}{\sqrt{3} Z_k} \qquad (1)$$

Where Z_k *(2)* is the equivalent short circuit impedance of the network. The considered equivalent network is illustrated in Figure 4.2. The equivalent short-circuit impedance for this network is;

$$Z_k = (R_{Qt} + R_{TK} + R_L) + j(X_{Qt} + X_{TK} + X_L) \qquad (2)$$

The supplying voltage of the short circuit current is $\frac{C_{max} U_n}{\sqrt{3}}$

Voltage factor C_{max} used for the calculation of maximum short circuit current that is 1,1 times of average value for the distributed power system.

4.2.2 Steady-state current

The steady-state current *(3)* of a far from-generator fault can be assumed as equal to the subtransient short circuit current. For a fault near-to-generator, the symmetrical short-circuit current can be assumed as decay based on the type of generator which is asynchronous or synchronous (IEC, 2001). For a meshed network with several sources, it is valid to make the following approximation for both near-to-generator and far-from-generator faults.

$$I_k = I_k'' \tag{3}$$

4.2.3 Peak current

The short circuit currents can take the highest values rapidly. The peak *(4)* current in a radial network is calculated as

$$i_p = k\sqrt{2}I_k'' \tag{4}$$

k (5) is the value of the equivalent impedance of the components (X/R) along with a rate (Anderson, 1995).

$$k = 1{,}02 + 0{,}98e^{-3R/X} \tag{5}$$

4.2.4 Decaying DC component

The decaying DC component of the short circuit current *(6)* is calculated as;

$$i_{d.c.} = \sqrt{2}I_k''e^{-2\pi ftR/X} \tag{6}$$

f is the system frequency and *t* is the time. If $t = 0$, the value of A in Figure 4.3 and 4.4 is obtained (Anderson, 1995).

4.2.5 Symmetrical breaking current

The symmetrical breaking current I_b *(7)* will depend on the network structure, i.e. meshed or radial, as well as the location of the fault, i.e. far-from-generator or near-to-generator. The symmetrical current can be approximated as

$$I_b = I_k'' \tag{7}$$

for both far-from- and near-to-generator faults. By approximating the symmetrical current as the subtransient current, a conservative value is obtained (Tleis, 2008).

4.3 Short Circuit Fault Current

In the power system, the short circuits occur related to the various reasons like, equipment failure, lightning strikes, falling of branches or trees on the transmission lines, switching surges, insulation failures and other electrical or mechanical causes. All of them are named as faults in power systems. A fault usually happens in high current flowing at lines and if an efficient protection is not taken, it may result in damages in the power system devices.

The short circuits can occur on a three-phase system in many ways. The devices or equipments for protection must have the capacity to break or withstand any type of short circuit. The magnitude of the fault currents depends on the internal impedance of the generator, in addition to the impedance of the intervening circuit. As discussed earlier the impedance of the rotating machine is not constant under short circuit condition (Das, 2002).

4.3.1 Nature of fault current

The short circuit current can be either symmetrical or asymmetrical. If the envelopes of the peaks of the current waves are symmetrical about the zero axis, the envelope is a straight line drawn through the peaks of the waves.

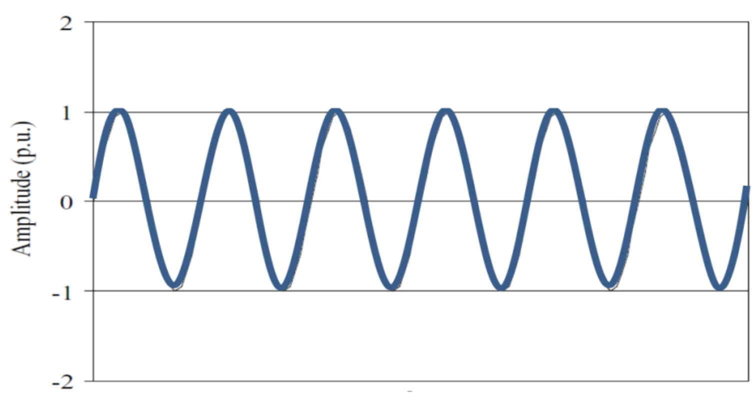


Figure 4.5 Symmetrical AC current wave

If the envelopes of the peaks of the current waves are asymmetrical about the zero axis, the envelope is not a straight line (Angelopoulos, 2004).

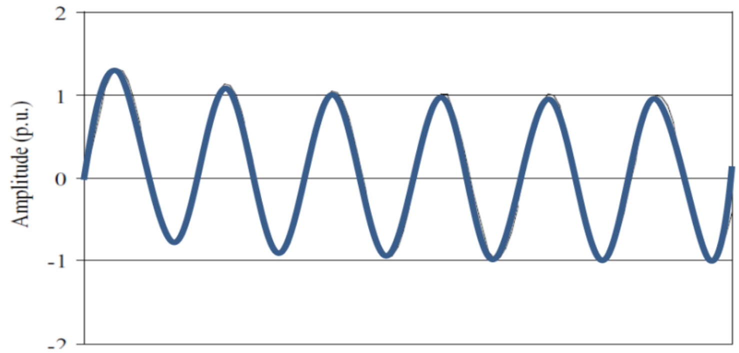


Figure 4.6 Asymmetrical AC current wave

Figures 4.5 and 4.6 show typical symmetrical and asymmetrical AC waves. In the usual industrial power systems, the applied or generated voltages are of sine wave form. When a short circuit occurs, substantially sine wave short circuits currents occur. In ordinary power circuits, the reactance of the circuit is negligible compared with the resistance of the circuit. The short circuit current power factor is determined by the ratio of resistance and reactance of the circuit.

If in a circuit basically including reactance, a short circuit occurs at the peak of the voltage wave, the short circuit current will start at zero and create a sine wave which is symmetrical about the zero axis. It is called symmetrical short-circuit current. If in the same circuit, a short-circuit occurs at the zero point of the voltage wave, the current will start at zero but cannot follow a sine wave symmetrically about the zero axis because such a current will be in phase with the voltage. This can happen in the situation in which the current is displaced from the zero axis (Angelopoulos, 2004).

In the state that the pre-fault system current cannot change sharply, it causes an unidirectional component in the fault current depending on the exact instance of the occurrence of the short circuit.

This unidirectional current component often referred to as DC offset, decays with time exponentially (Ahnlund, 2014).

The amount of offset that will occur in a fault current waveform depends on the time at which the fault occurs on the AC voltage waveform and the network resistances and reactances.

In a completely reactive network, the current can have any offset from none to whole, depending on the time of its beginning and the offset will go on. In a completely resistive system, a fault will have no offset in the current waveform. A network containing both resistances and reactances will generally begin with some offset in the current (up to full) and gradually the current will become symmetrical around the zero axis **(**Ahnlund, 2014).

4.3.2 **Types of fault current**

Most of the short circuit faults in industrial and commercial power systems can be classified in two categories depending on the nature of the fault current waveform (Das, 1998).

- Symmetrical or balanced faults
- Asymmetrical or un-balanced faults

The asymmetrical faults can be further classified in three major types

- Single Line-to-Ground fault
- Double Line fault
- Double Line-to-Ground fault

4.3.2.1 **Three phase faults**

The fault current magnitude is balanced equally within the three phases for a balanced symmetrical system. While this type of fault is not seen very often, its results are used for protective device selection, because this fault type generally is realized for the maximum short-circuit current values. Figure 4.7 provides a graphical representation of a three-phase fault (Ramachandran, 2011). Because the network is balanced, it is solved on a per-phase basis. The other two phases carry identical current except for the phase shift.

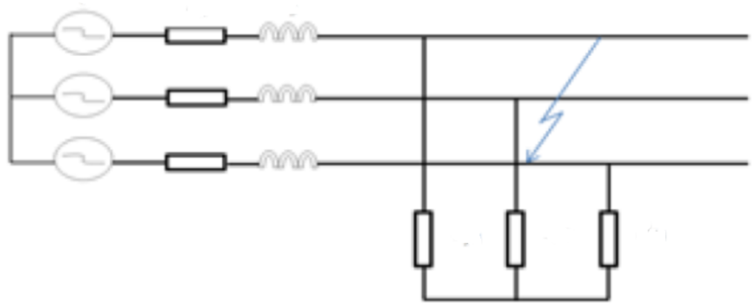


Figure 4.7 The three phase fault

The three-phase earth fault can also occur when the three lines come in contact with ground, the system will still stay in balance even if the fault involves a ground impedance (Das, 2002).

4.3.2.2 The single line-to-ground fault

In Figure 4.8, line-to-ground faults are the most common types of faults, which are usually the least disturbing for the system. The current in the faulted phase can range from near zero to a greater value slightly than the three-phase fault current. The line-to-ground fault current magnitude is determined by the method in which the system is grounded and the impedance of the ground return path of the fault current (IEC, 2001).

It is necessary to have calculation techniques of symmetrical components for calculating of the certain line-to-ground fault magnitudes.

Line-to-ground fault current magnitudes in distribution systems with a good grounded system will be nearly equal to the three-phase fault current magnitudes. It is required detailed ground return path impedance knowledge and specific calculation methods for finding line-to-ground fault currents on long conductors or transmission lines (Tleis, 2008).

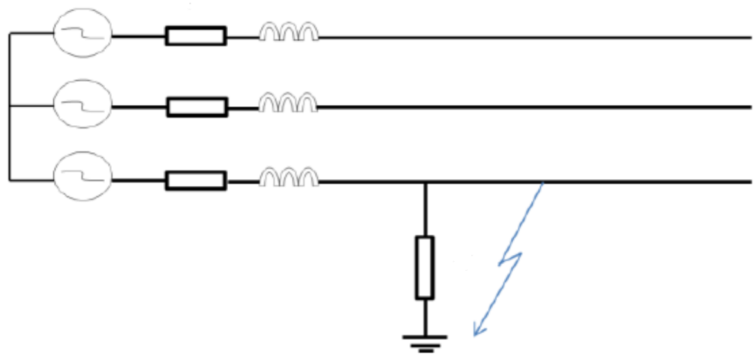


Figure 4.8 The line to ground fault

It is usual to use three phase short-circuit analysis while determining the maximum possible magnitudes of fault currents. There are exceptions when single line-to-ground short-circuit currents go over three-phase short-circuit current levels when they occur in the vicinity of

- A solidly grounded synchronous machine
- The solidly grounded WYE side of a Delta-WYE transformer of the three phase core design
- The grounded WYE side of a Delta-WYE autotransformer
- The grounded WYE, grounded WYE, Delta-Tertiary of a three winding transformer (Tleis, 2008 - Das, 2002)

4.3.2.3 **The phase to phase fault**

In Figure 4.9, phase-to-phase faults are more widespread than three-phase faults and have fault currents that are about 87% of the three-phase bolted fault current. This type of fault is not balanced in the three phases and its fault current is rarely calculated for equipment selections since it does not give the maximum fault current magnitude. The phase to phase fault current can be calculated by multiplying the three-phase value by 0.866, on the condition that the impedances are equal (Anderson, 1995).

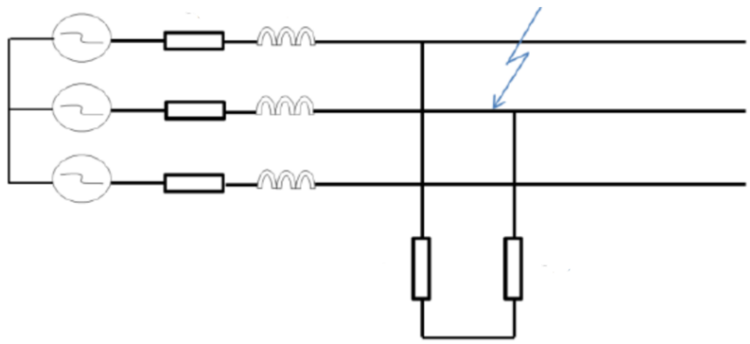


Figure 4.9 The phase to phase fault

4.3.2.4 **The phase to phase ground fault**

In Figure 4.10, the phase-to-phase ground fault is a rating of greatness, which is proportioned according to line-to-ground fault.

This is a kind of unbalanced fault. The magnitudes of double line-to-ground fault currents are usually greater than those of line-to-line faults, but are less than those of three-phase faults (Tleis, 2008- IEC, 2001). It is needed the symmetrical components analysis for the calculation of double line-to-ground fault currents. Because the impedance of the ground return path will influence the result, it should be provided if it is possible.

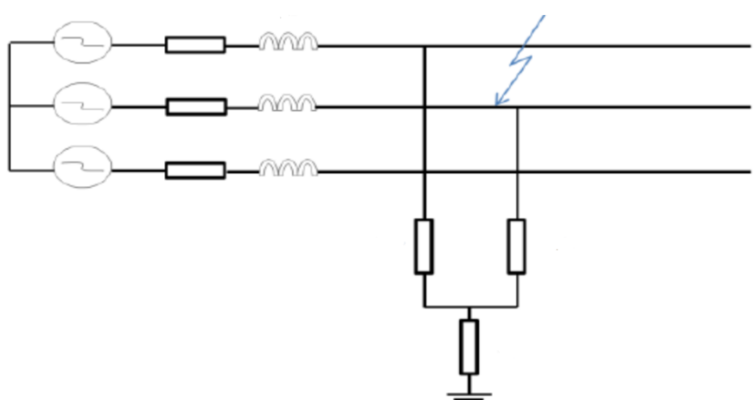


Figure 4.10 The phase to phase ground fault

CHAPTER 5

SIMULATION

5.1 Simulation Software

PSS/SINCAL software by SIEMENS has been used for the analysis and simulation in thesis. PSS/SINCAL is software with designing tools for power system analysis. Power systems analysis includes the short circuit analysis, the power flow, dynamic analysis, harmonic analysis, protection, reliability and contingency analysis.

The short circuit calculations for the network are simulated with complex impedances but controllers and machines are modelled as differential equations. To consider unsymmetrical faults in addition to symmetrical faults such as three-phase short circuits, PSS/SINCAL uses symmetrical and asymmetrical components to find general disturbance case (Siemens, 2013).

The Electromagnetic Transients (EMT) let the designer use the differential equations to model networks, machines and controllers. It offers a complete solution for all electromechanical and electromagnetic phenomena, including unsymmetrical sequences (Siemens, 2013).

These calculation methods are used for planning, designing and managing operations in electricity transmission and distribution networks as well as industrial networks. The following basic modules are available

- Short Circuit 3-Phase
- Short Circuit 2-Phase and Ground Circuit 2-Phase
- Ground Circuit 1-Phase

The short circuit calculations are required for assessing the correct ratings for the maximum fault currents of network and also for protection coordination for minimum fault currents. PSS/SINCAL can calculate one-phase ground faults, two-phase short circuit and ground faults, as well as three phase short circuits for individual nodes or entire subnetworks. This means, the current disturbance in the network can be determined for any fault condition.

Key features of short circuit simulation (Siemens, 2013);

- Calculations with symmetrical components
- Arc impedances can be considered
- Key values are I_k'', i_p, S_k'', U_0, Z_0/Z_1
- i_p can be calculated either according to radial or meshed networks or the equivalent frequency method
- Neutral grounding
- Phase shifts in transformers
- Calculations throughout all network levels at the same time
- Calculations of all currents and voltages in the whole network for a single fault location
- Calculations of faults at every node in specified network levels simultaneously
- Various reports for all nodes, all fault locations and all network levels

5.2 Short Circuit Calculation with PSS/SINCAL Software

While performing steady-state short circuit calculations in PSS/SINCAL, there is a number of different calculation standards.

The available standards are (Siemens, 2013);

- VDE 0102/1.90 - IEC 909
- IEC 909/2001 - VDE 0102/2002
- IEC 61363-1/1998
- ANSI
- G74

The short circuit model used by each system component will be different depending on the selection of the standards about the calculation methods. Moreover, each method has a range of advanced calculation options. There are some basic input parameters common to all methods. These are listed below (Ahnlund, 2014);

• Fault Type

There are numerous available fault types, ranging from three phase to single phase including short-circuits, faults to neutral and neutral to ground. In this thesis, three phase fault and phase to phase fault have been considered.

• Fault Impedance

The designer has the option to select both the reactance, X_f and resistance R_f of the fault. This impedance represents the shorted path caused by the fault. In addition to a standard representation of the fault impedance, there is an extra fault impedance option available, which takes the line-to-earth, as well as the line-to-line impedance into consideration. For this thesis, only the standard representation of fault impedances has been considered.

• Fault Location

The simulated fault can be placed at any terminal, bus or along the length of any line in the system. In this thesis, faults located directly at bus, terminal connections and transmission line have been considered.

5.3 Modelling of The Power Plant System

A typical industrial power plant has been modelled for simulation and analysis in PSS/SINCAL software as shown in Figure 5.1. The modelling has been based on the real loads of the plants, the real power of the transformers, the motors, the generators and the impedance of the lines.

This plant has been modelled as an industrial system including electrical distribution system directly connected five plants of an industrial zone. The power system is connected to the grid by one line at 34,5 kV level at Batı Anadolu Power Transmission Line I–II lines. The distribution to the plants is at 34,5 kV voltage level and it is connected with 150 meter 477 MCM cable and about 1000 meter 4x1x 95 mm2 XLPE cable.

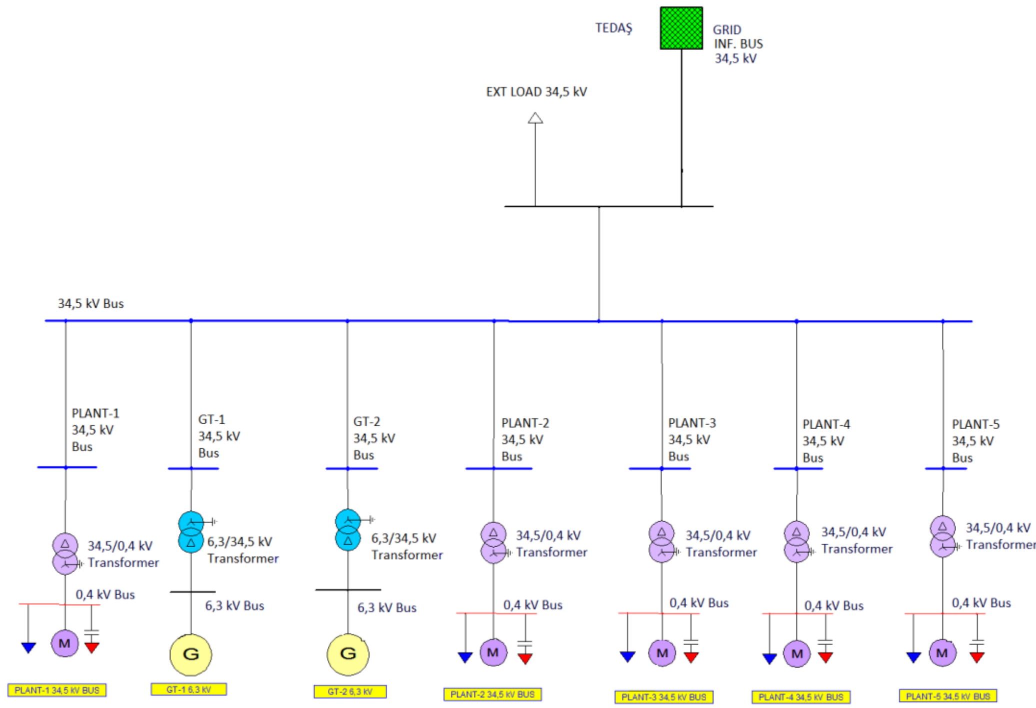


Figure 5.1 The power plant electrical system

The power plant has 2 Gas Turbines (GT) connected to the same 34,5 kV bus. Each turbine has 6,5 MW capacity and total power plant production capacity is 13 MW. Depending on the operation conditions of power plant and factories, either the power export or power import to the grid is possible.

There are five plants in industrial zone and each factory is supplied one by one by the cable feeders. Every plant has its own step-down transformer (34,5 kV / 0,4 kV) feeding each 0,4 kV factory bus.

The faults are simulated at the grid bus, 34,5 kV bus, Plant-1 34,5 kV bus, GT-1 34,5 kV bus, GT-2 34,5 kV bus, Plant-2 34,5 kV bus, Plant-3 34,5 kV bus, Plant-4 34,5 kV bus and lines.

CHAPTER 6

CASE STUDIES

6.1 Short Circuit Analysis Simulation of Cases

The different cases analyzed are a number of network configurations that are of interest to investigate. This section, three phase power system is likely phase to ground, phase-to-phase, two phase earth fault, earth contact and contactless earth three phase short circuit with PSS/SINCAL has been designed. The Simulation obtained in the voltage and the current graphs for each fault and faults compared with the actual failure conditions have been reviewed and made simulations.

In this thesis, it is assumed that the fault point is nearest grid bus that is infinite bus and there are three phase and phase-to-phase short circuit faults that are most severe faults in the power systems. The power system network configuration is shown in Figure 6.1.

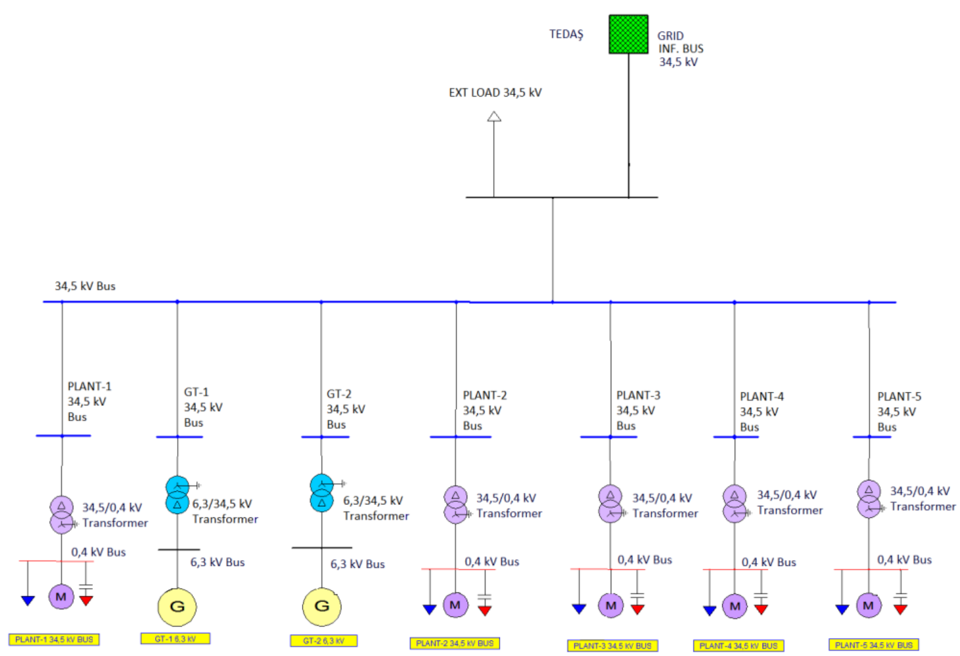


Figure 6.1 The power plant single line diagram

Several cases are simulated with different parameters and resulting effects on power system. According to the fault type, fault location, buses voltages and currents of generators and loads, many different cases may be obtained for simulations. In this thesis, four of them are selected and studied:

Case 1- Three phase ground fault in grid,

Case 2 - Phase to phase ground fault in grid,

Case 3 - Low voltage load three phase ground fault,

Case 4 - Phase to phase ground fault in island mode operation in power plant-1.

6.1.1 Case 1- three phase ground fault in grid

Case 1 is set up at normal operation, with contributions from the 34,5 kV grid and from the generators GT-1 and GT-2. The three phases ground fault circuit occurs at the transmission line between grid and coupling bus at the 200th msec and then the fault is cleared at the 280th msec. The power system network configuration is shown in Figure 6.2.

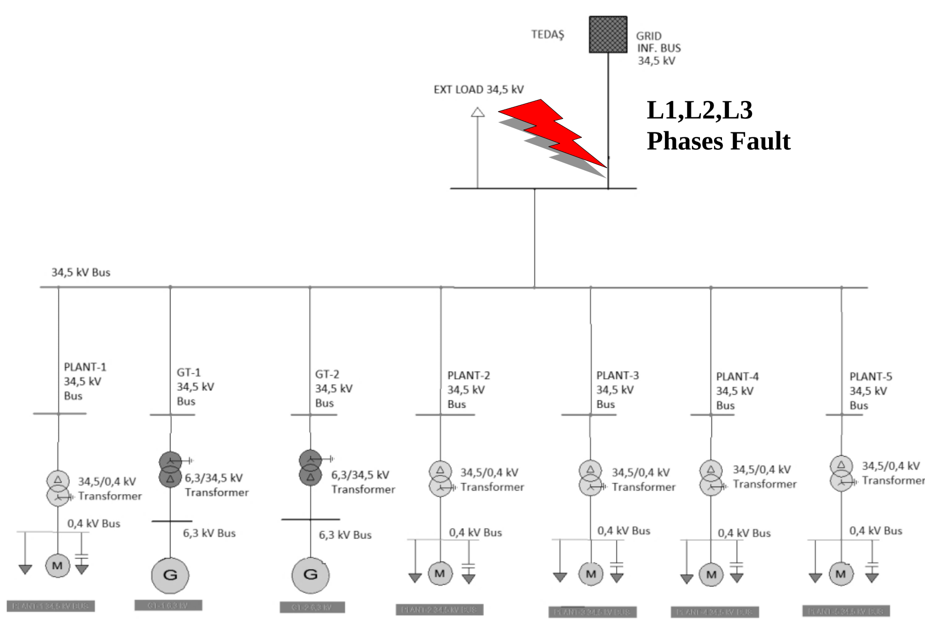


Figure 6.2 PSS/Sincal Prints screen - single line diagram for 3 phase ground fault

At the 200th msec after simulation system started, the three phases ground short circuit occurred and at the 280 msec, the short circuit was cleared. The simulation was lasted for 5 sec but all figures are shown between 0,1 sec and 0,4 sec for more details.

The voltage and current variations measured from the buses and the lines according to the time, when the short circuit at grid occurred, have been shown at below figures.

Grid Bus Voltage

It can be seen that there are voltage levels related to the fault in Figure 6.3.

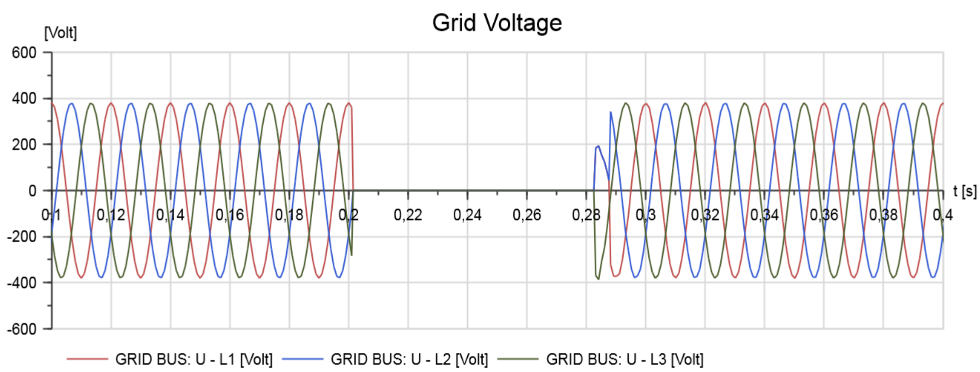


Figure 6.3 Grid voltage levels at three phases ground fault

After the three phases short circuit had occurred, the voltages of L1, L2 and L3 phases sharply dropped to zero volt value. The fault was cleared at the 280th msec but 10 msec after this, the system became steady-state.

Grid Connection Line Current

The current level during three phases ground fault can be seen from graphs in Figure 6.4 and 6.5.

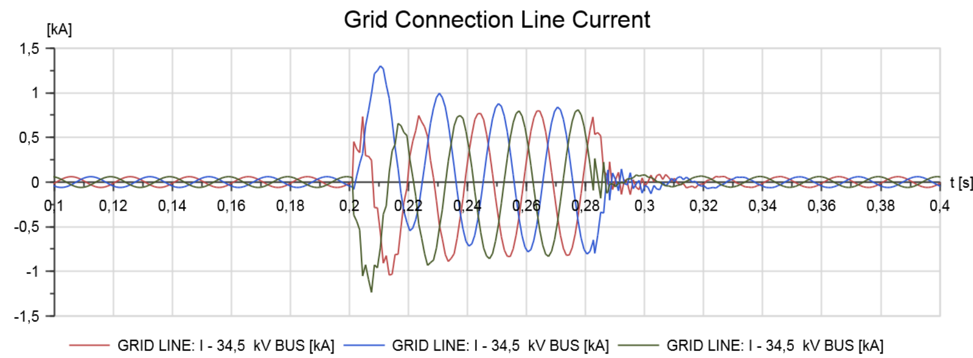


Figure 6.4 Grid connection line current levels at three phases ground fault

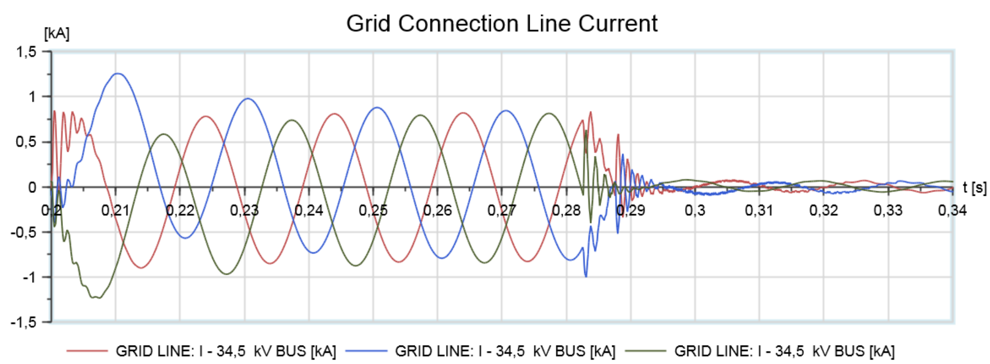


Figure 6.5 Grid connection line current detail waveform at three phases ground fault

When the fault occurred, the currents of L1, L2 and L3 phases sharply increased from nominal value to 13 times. The currents of L1, L2 and L3 phases gradually decreased until the fault was cleared. After the 280th msec, the currents decreased fast to the magnitude about nominal level.

The system became steady-state at the 330th msec. This means; 50 msec later the fault was cleared, the system became steady-state.

It was seen that there was a great increase in the fault current in the node grid connection line. The reason of this was that the fault location was very near the grid source.

34,5 kV Bus Voltage

The resultant waveform for the three phases ground fault is shown in Figure 6.6.

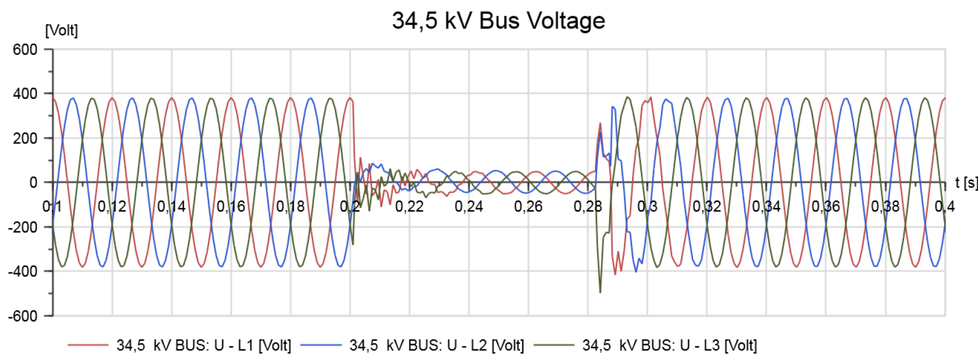


Figure 6.6 34,5 kV Bus voltage levels at three phases ground fault

The voltages of L1, L2 and L3 phases dropped to about 95 volt value. The voltage levels was not zero because the DG sources (GT-1 and GT-2 generator) was very near 34,5 kV bus.

Plant-1, Plant-2, Plant-3, Plant-4, GT-1 and GT-2 Voltages

The voltage levels during the fault can be seen as in the graphs Figure 6.7, 6.8, 6.9, 6.10, 6.11 and 6.12.

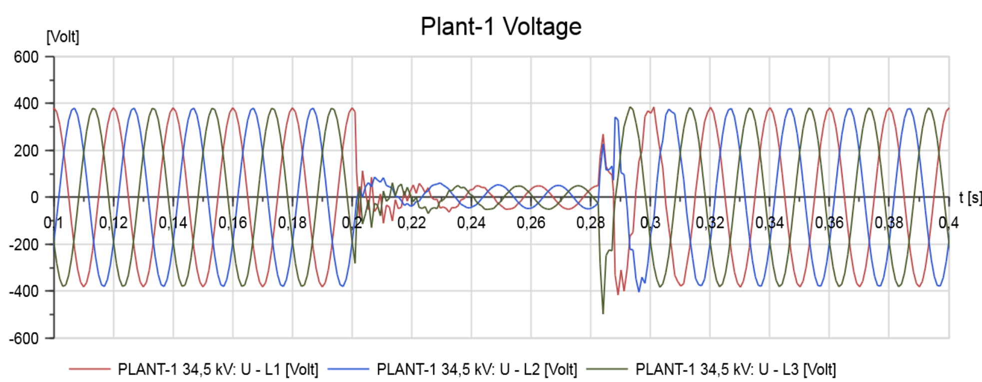


Figure 6.7 Plant-1 voltage levels at three phases ground fault

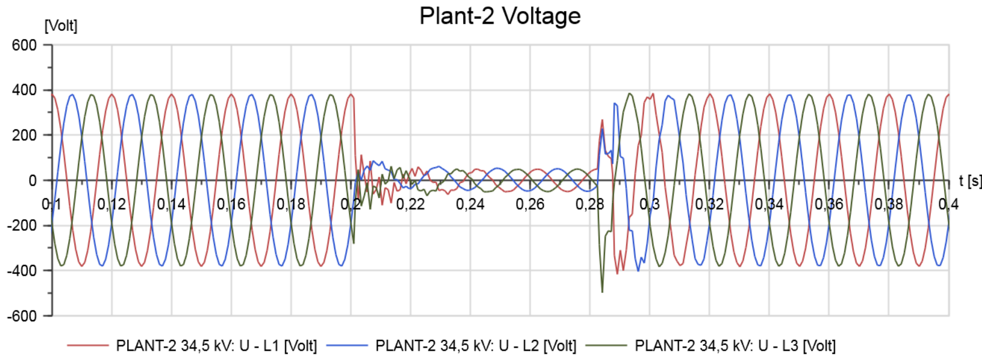


Figure 6.8 Plant-2 voltage levels at three phases ground fault

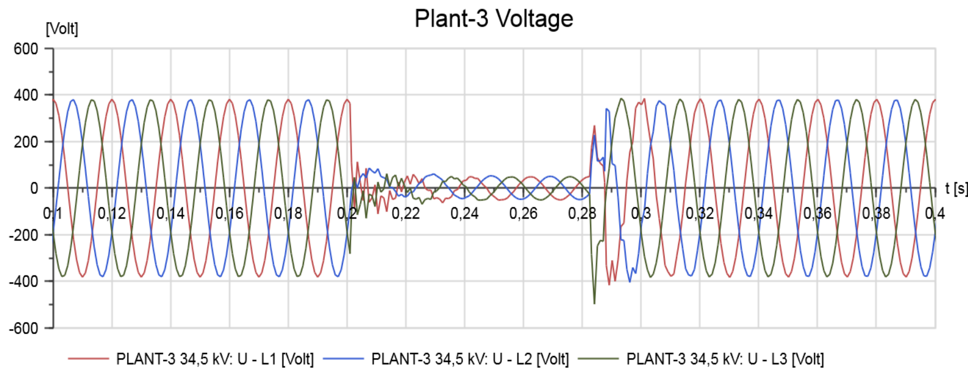


Figure 6.9 Plant-3 voltage levels at three phases ground fault

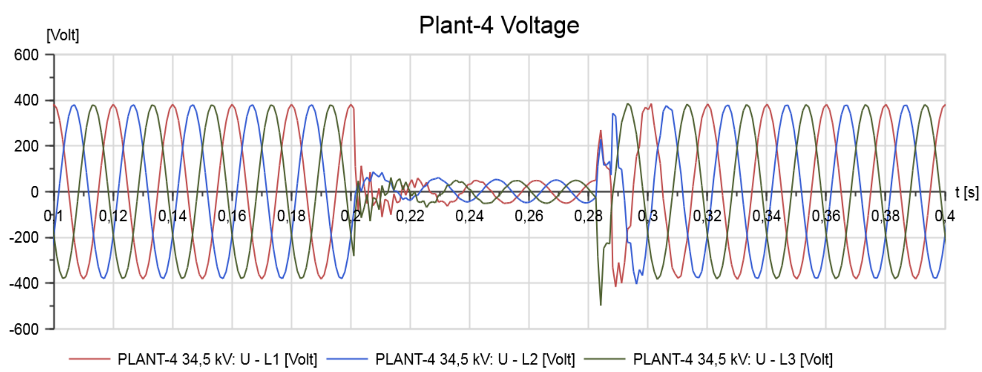


Figure 6.10 Plant-4 voltage levels at three phases ground fault

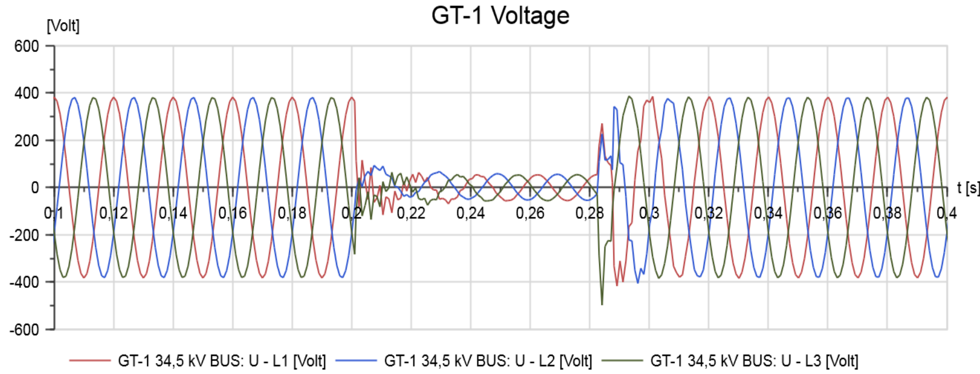


Figure 6.11 GT-1 voltage levels at three phases ground fault

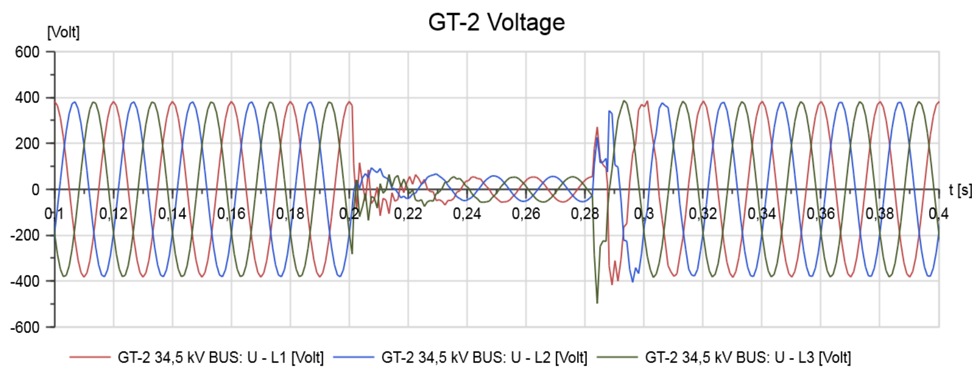


Figure 6.12 GT-2 voltage levels at three phases ground fault

The voltages of L1, L2 and L3 phases dropped to about 95 volt value. The voltage levels were not zero as they were expected because the DG sources (GT-1 and GT-2 generator) were very near 34,5 kV bus and they were also directly connected to 34,5 kV bus. For this reason, these buses were the same voltage levels as expected.

Plant-1, Plant-2, Plant-3 and Plant-4 Currents

Figure 6.13, 6.14, 6.15 and 6.16 currents level during three phases ground fault can be seen in graphs.

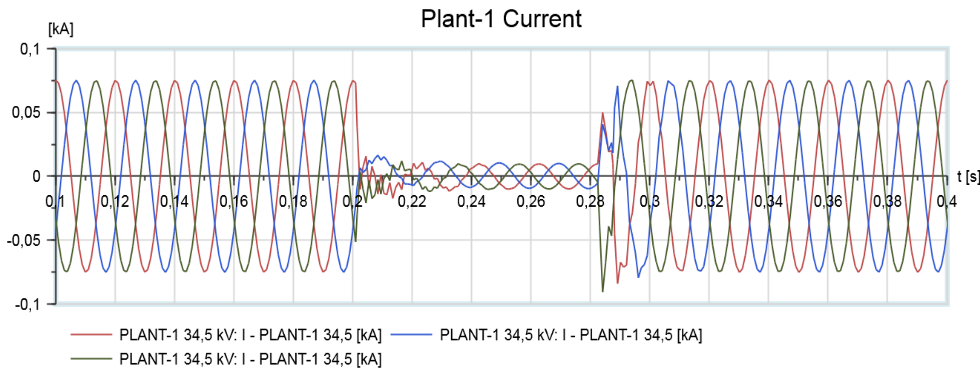


Figure 6.13 Plant-1 curret levels at three phases ground fault

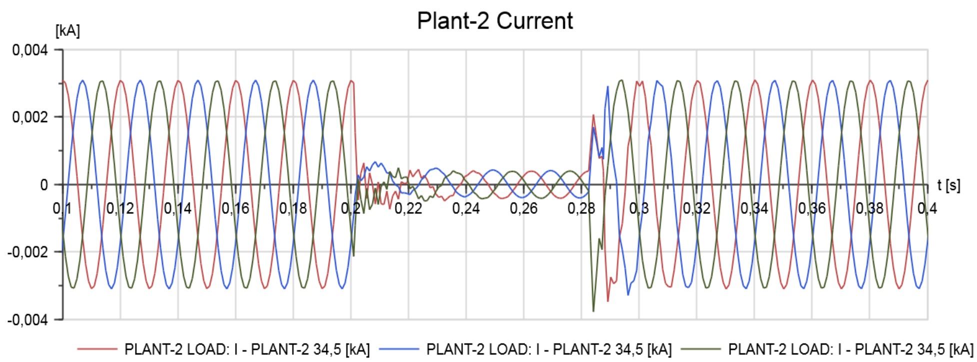


Figure 6.14 Plant-2 curret levels at three phases ground fault

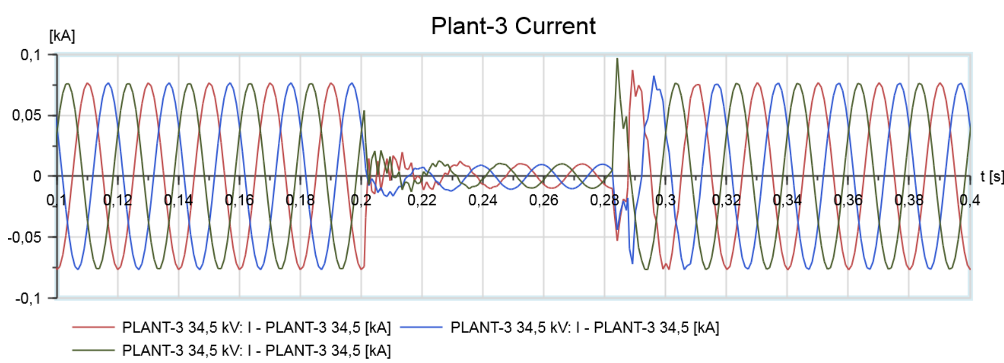


Figure 6.15 Plant-3 curret levels at three phases ground fault

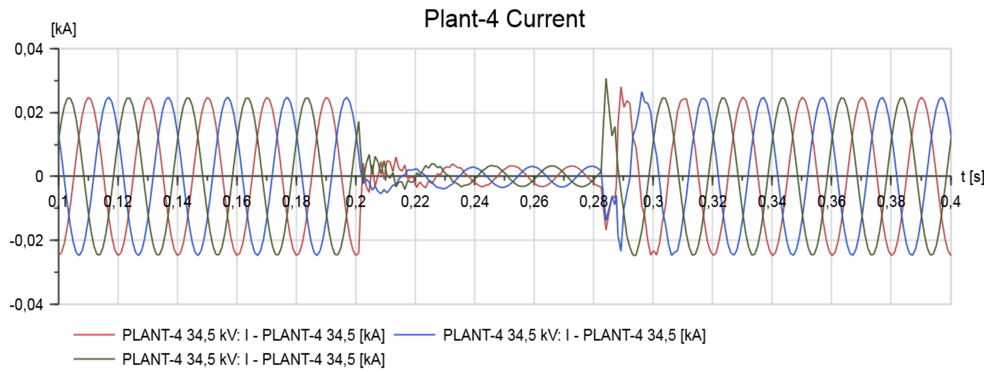


Figure 6.16 Plant-4 curret levels at three phases ground fault

All plants were connected to the same bus. Therefore, there was no voltage level difference in the buses of each plant. All of the obtained current waveforms were the same shape as expected. Because all plants had different loads, they had different current level magnitude.

GT-1 and GT-2 Currents

GT-1 and GT-2 current waveforms are shown in Figure 6.17 and 6.18.

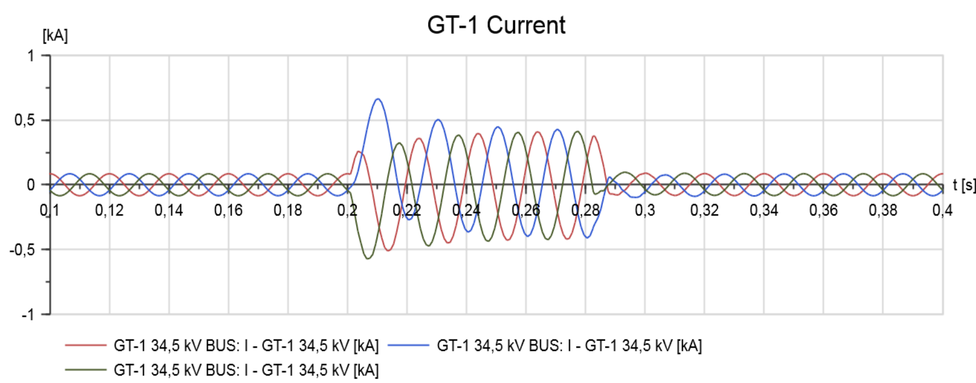


Figure 6.17 GT-1 curret levels at three phases ground fault

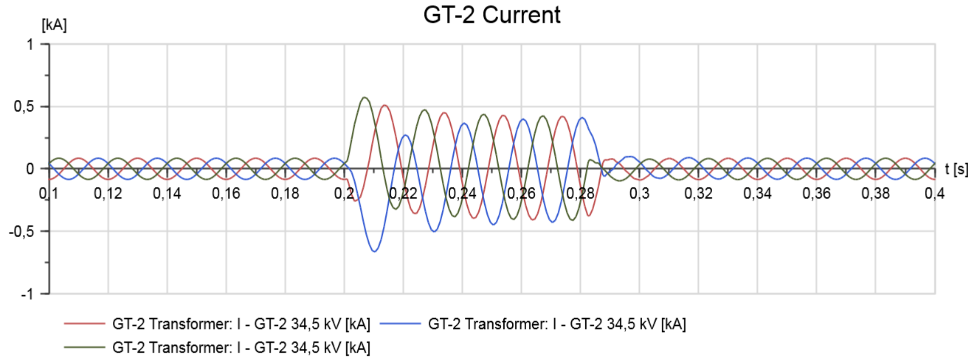


Figure 6.18 GT-2 curret levels at three phases ground fault

When the short circuit occurred, the currents of L1, L2 and L3 phases sharply increased from nominal value to 5 times. The currents of L1, L2 and L3 phases gradually decreased until the fault was cleared. After the 280th msec, currents decreased fast to the magnitude about nominal level. The system became steady-state the 330th msec. This means; 50 msec later after the fault was cleared, the system was became steady-state. Because GT-1 and GT-2 fed the fault from the opposite direction, there was a great increase in the fault currents in GT-1 and GT-2.

Plant-1, Plant-2, Plant-3, Plant-4, GT-1 and GT-2 Frequency Deviations

The frequency deviation during the fault is shown in the graphs in Figure 6.19, 6.20, 6.21, 6.22, 6.23, and 6.24.

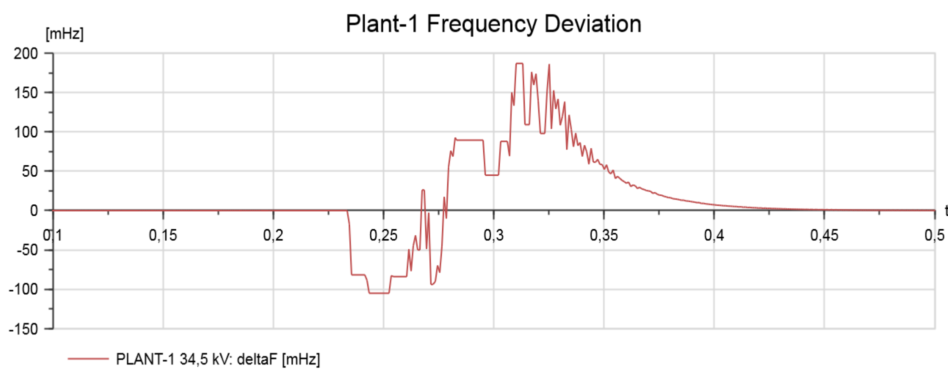


Figure 6.19 Plant-1 frequency deviation at three phases ground fault

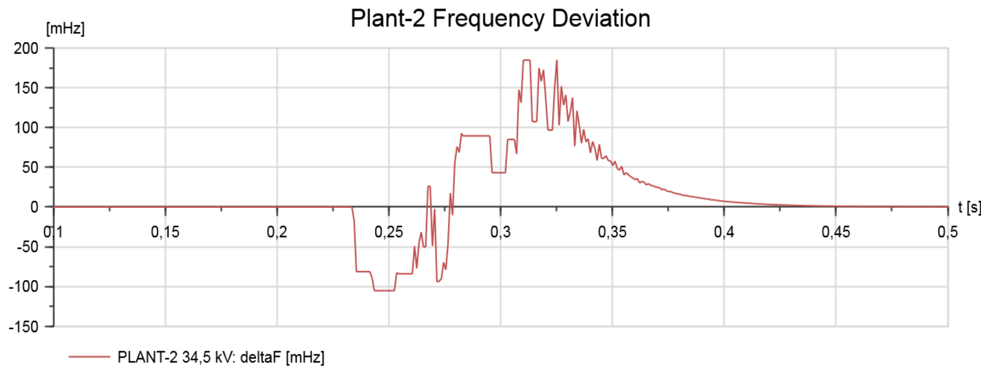


Figure 6.20 Plant-2 frequency deviation at three phases ground fault

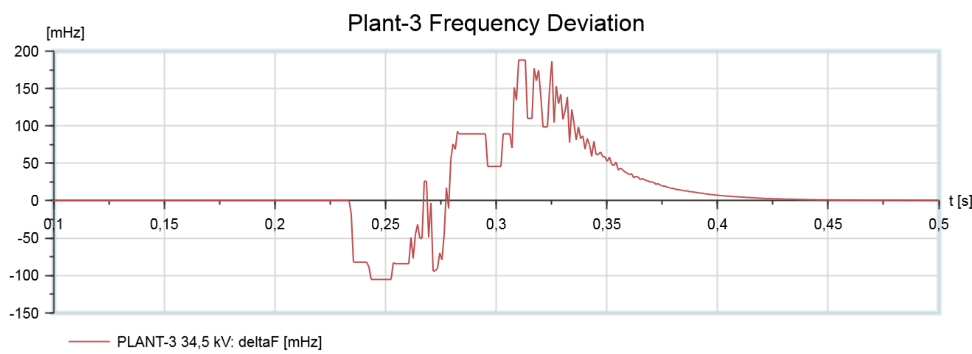


Figure 6.21 Plant-3 frequency deviation at three phases ground fault

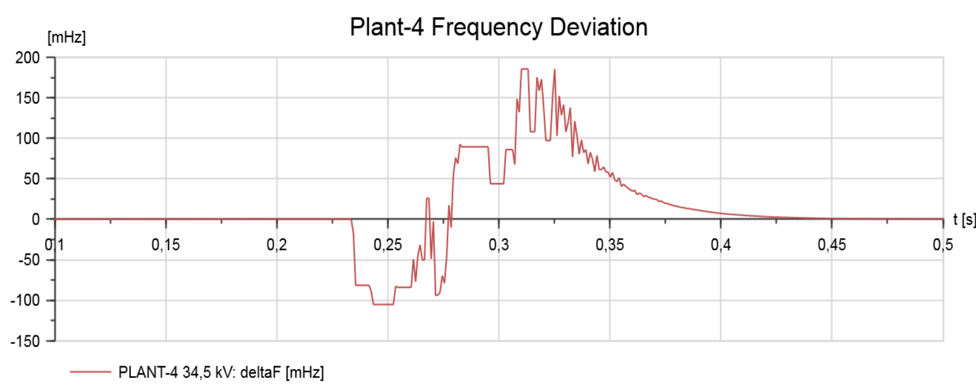


Figure 6.22 Plant-3 frequency deviation at three phases ground fault

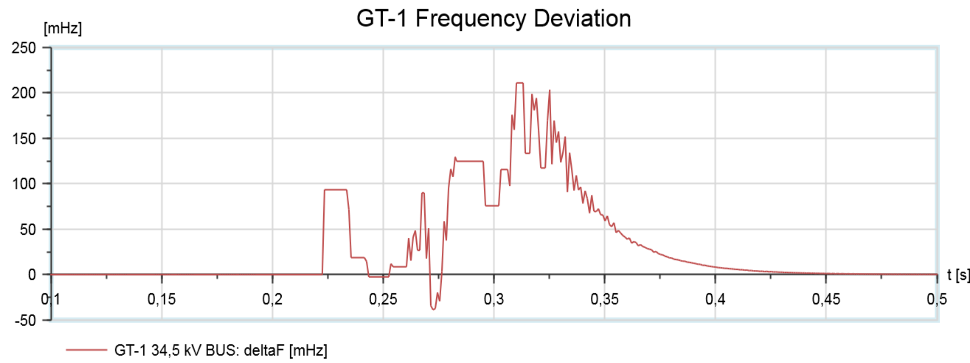


Figure 6.23 GT-1 frequency deviation at three phases ground fault

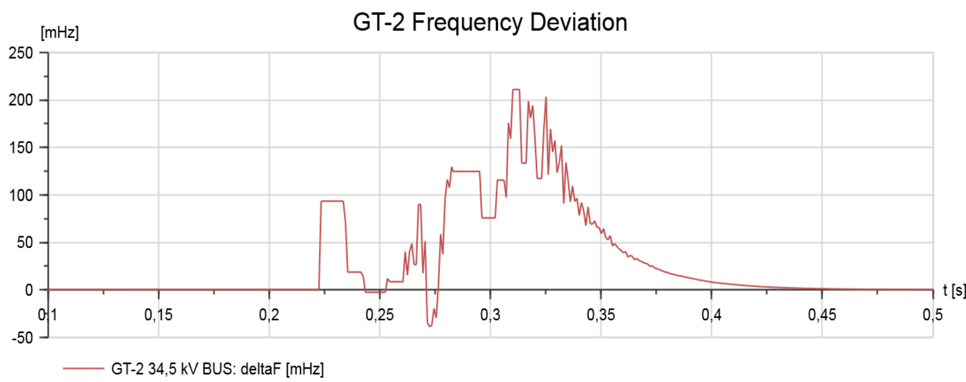


Figure 6.24 GT-2 frequency deviation at three phases ground fault

The frequency deviation levels reached about 210 mHz in GT-1 and GT-2. At the same time, the frequency deviation increased to 180 mHz in Plant-1, Plant-2, Plant-3 and Plant-4. Although all waveforms were similar, the magnitudes of the frequency deviation of GT-1 and GT-2 were different from the plants as expected.

The fault was simulated by the simulation software as it was expected.

6.1.2 Case 2 –The phase to phase ground fault in grid

This case is very similar to Case-1 and the only difference when, it is compared to case 1, is that the fault type is phase to phase. The phase-to-phase ground fault circuit occurs at the transmission line between grid and coupling bus at the 200th msec and then the fault is cleared at the 280th msec. The power system network configuration is shown in Figure 6.25.

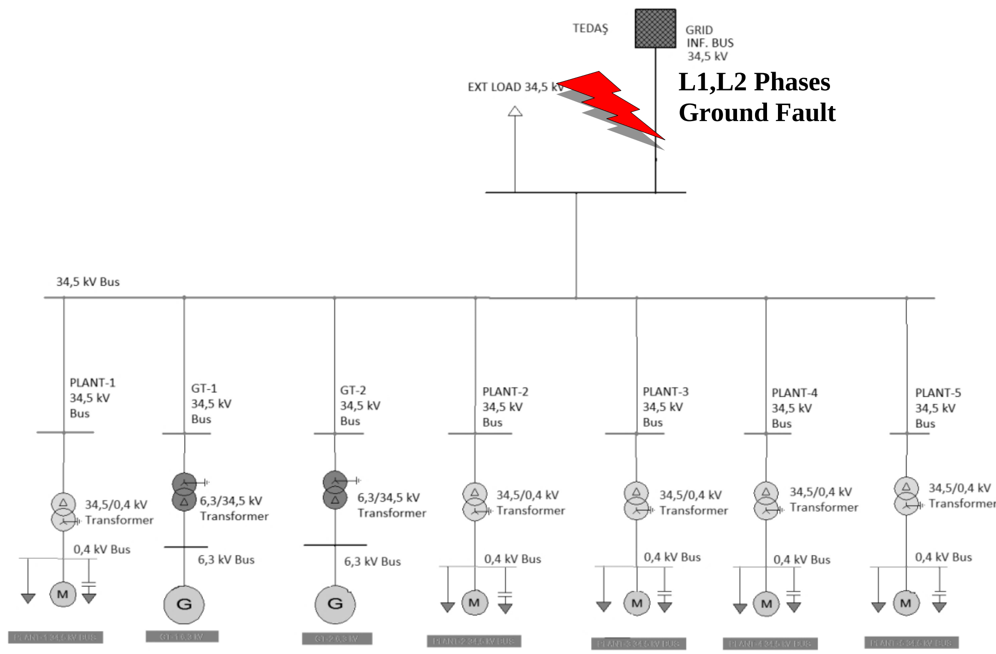


Figure 6.25 PSS/Sincal print screen - single line diagram for phase to phase ground fault

At the 200th msec after simulation system started, the phase-to-phase ground short circuit occurred and at the 280th msec, the short circuit was cleared. The simulation lasted for 5 sec. but all figures were shown between 0,1 sec and 0,4 sec for more details.

The voltage and current variations measured from the buses and the lines according to the time, when a short circuit at grid occurred, have been shown at below figures.

Grid Bus Voltage

It can be seen that there are voltage levels about the fault in Figure 6.26.

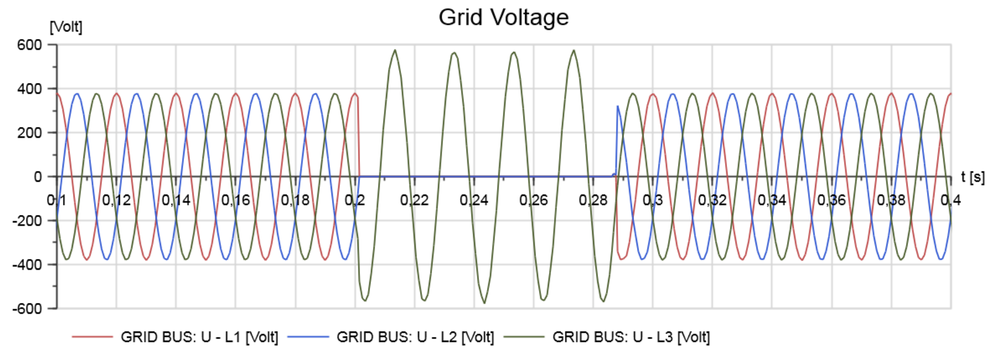


Figure 6.26 Grid voltage levels at phase to phase ground fault

After the phase (L1) to phase (L2) short circuit had occurred, he voltages of L1 and L2 phases sharply dropped to zero volt value. At the same time, L3 phase voltage raised about 600 volt as expected and during the fault, L3 phase remained at fixed value 600 volt. The fault was cleared at the 28thmsec but 10 msec. After the clearing, the system became steady-state.

Grid Connection Line Current

The current levels during the fault can be seen in Figure 6.27.

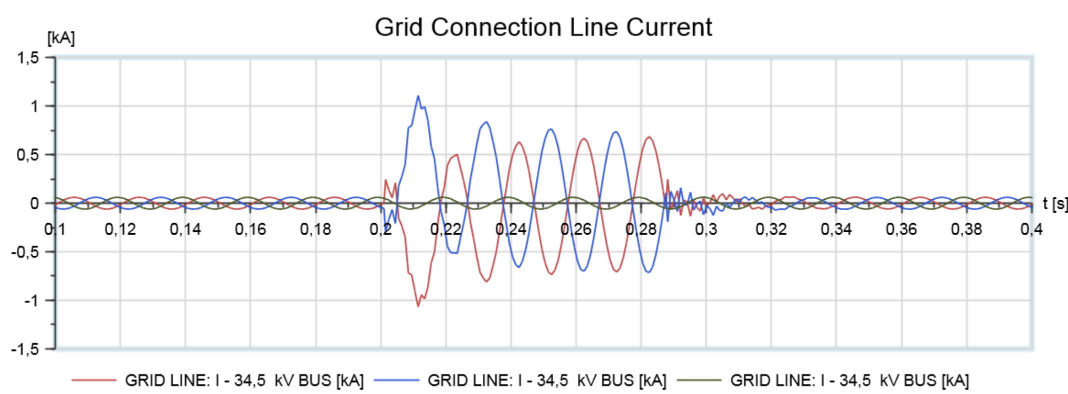


Figure 6.27 Grid connection line current levels at phase to phase ground fault

When the short circuit occurred, the currents of L1 and L2 phases sharply increased from nominal value to 11 times. The currents of L1 and L2 phases gradually decreased until the fault was cleared while L3 phase current value continued normally. The system became steady-state at the 330 rd msec. This means; 50 msec later after the fault was cleared, the system became steady-state.

It can be said that there was a huge increase in the fault current in the node grid connection line. The reason of this was that the fault location was very near the grid source.

34,5 kV Bus Voltage

The waveform obtained from the simulation for this fault is shown in Figure 6.28.

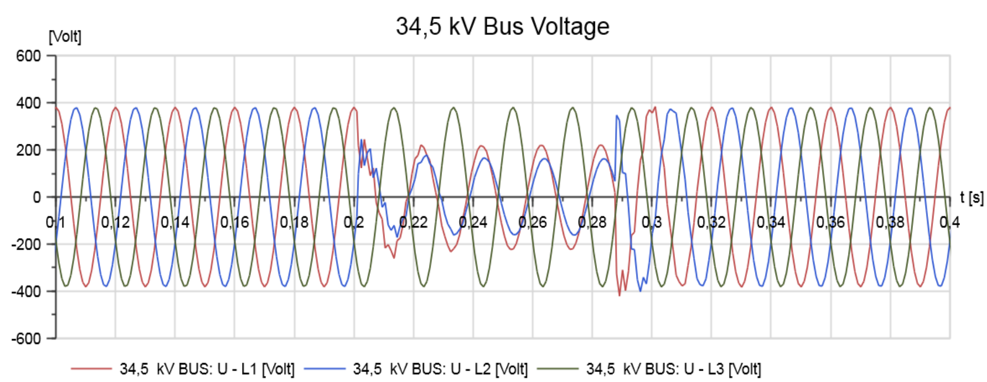


Figure 6.28 34,5 kV Bus voltage levels at phase to phase ground fault

The voltages of L1 and L2 phases dropped to about 200 volt value. The voltage levels were not zero as expected. There was no deviation voltage of L3 phase since the DG sources (GT-1 and GT-2 generator) were very near 34,5 kV bus.

Plant-1, Plant-2, Plant-3, Plant-4, GT-1 and GT-2 Voltages

The voltage levels during the fault are shown in Figure 6.29, 6.30, 6.31, 6.32, 6.33 and 6.34.

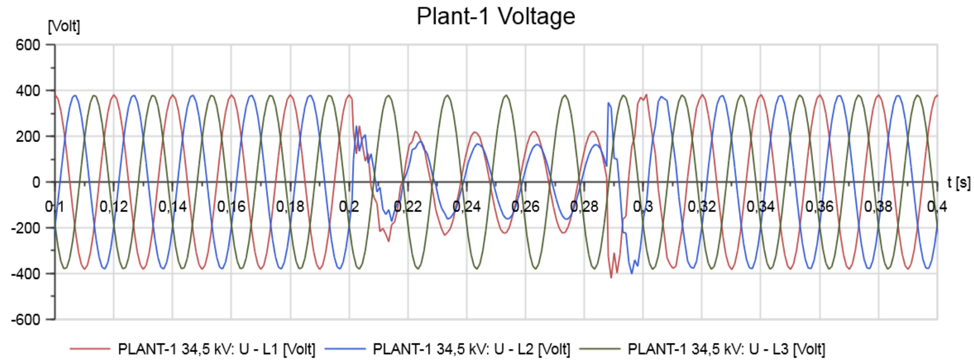


Figure 6.29 Plant-1 voltage levels at phase to phase ground fault

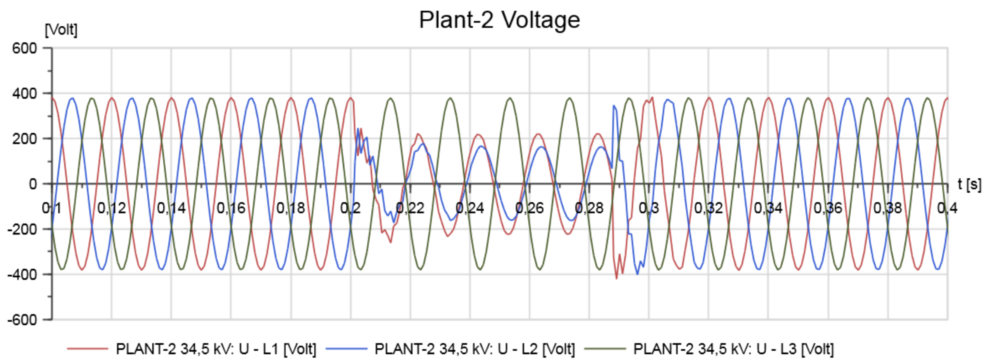


Figure 6.30 Plant-2 voltage levels at phase to phase ground fault

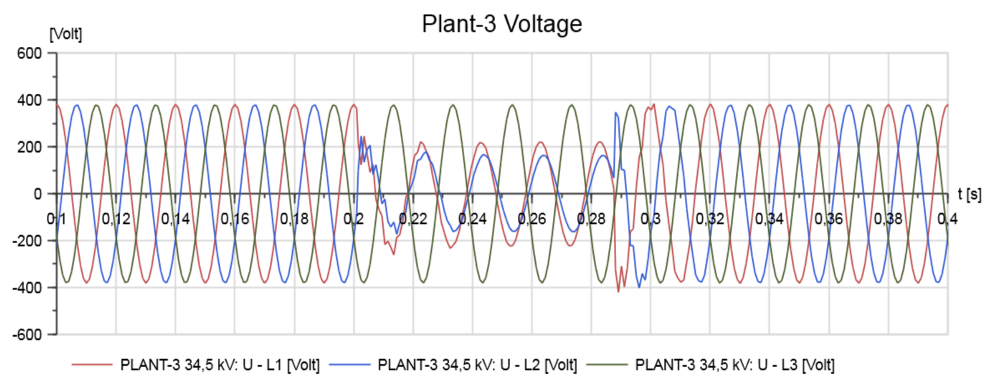


Figure 6.31 Plant-3 voltage levels at phase to phase ground fault

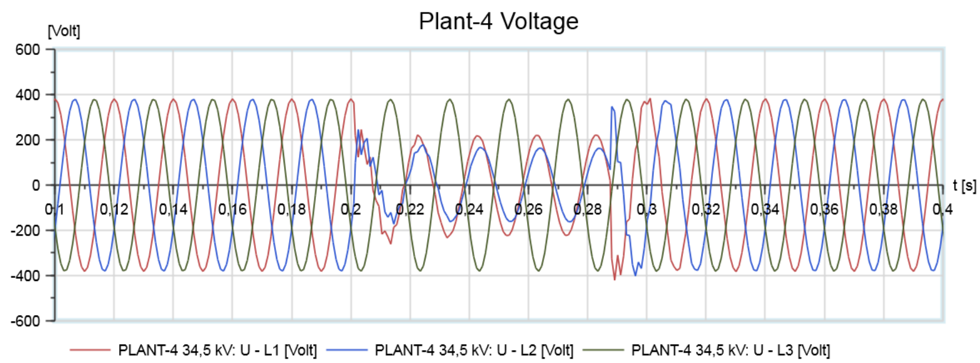


Figure 6.32 Plant-4 voltage levels at phase to phase ground fault

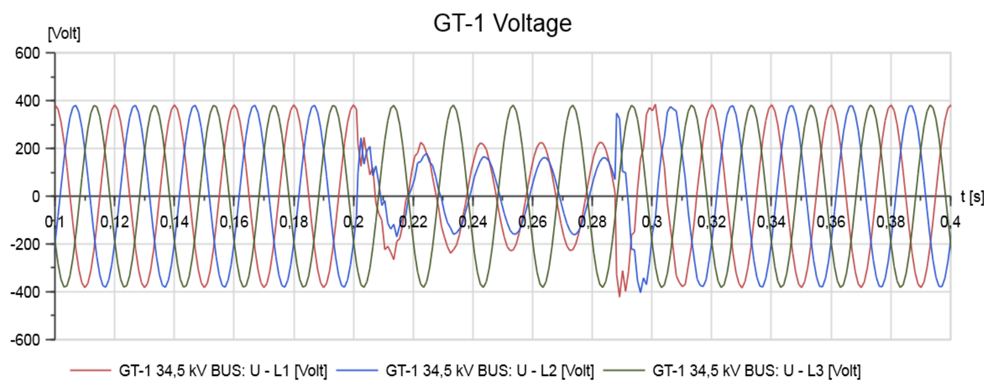


Figure 6.33 GT-1 voltage levels at phase to phase ground fault

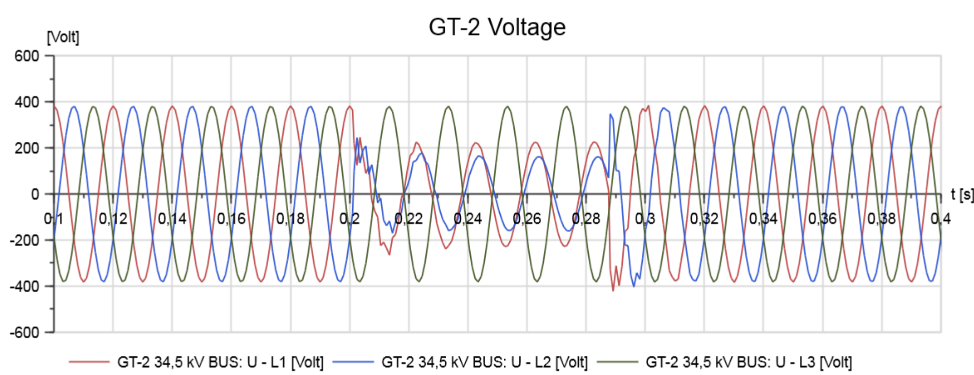


Figure 6.34 GT-2 voltage levels at phase to phase ground fault

Similarly 34,5 kV bus voltage level, the voltages of L1 and L2 phases dropped to about 200 volt value. The voltage levels were not zero as they were expected because the DG sources (GT-1 and GT-2 generator) were very near 34,5 kV bus and they were also directly connected to 34,5 kV bus. For this reason, these buses were the same voltage levels as they were known.

Plant-1, Plant-2, Plant-3, and Plant-4 Currents

The current levels during the fault can be seen in Figure 6.35, 6.36, 6.37 and 6.38 graphs below.

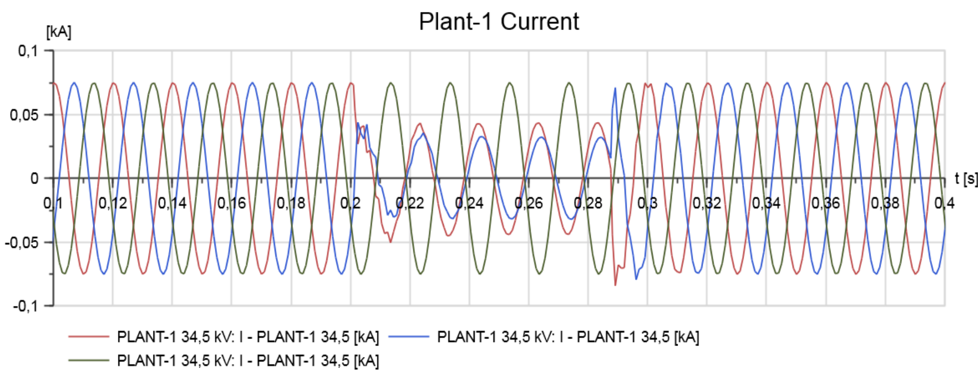


Figure 6.35. Plant-1 curret levels at phase to phase ground fault

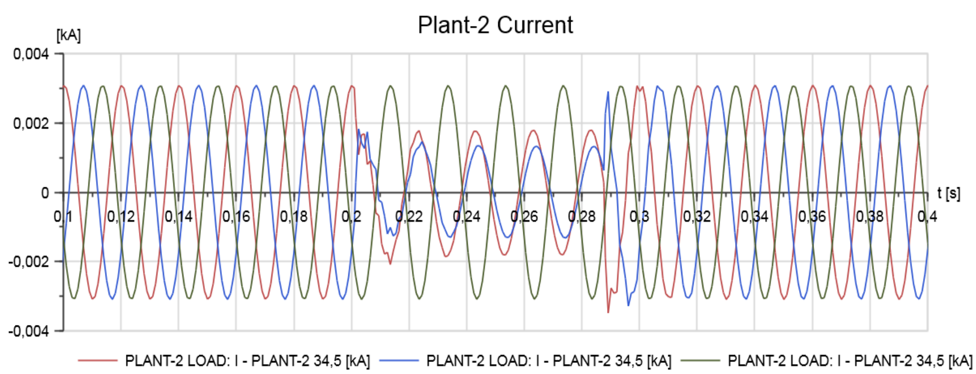


Figure 6.36 Plant-2 curret levels at phase to phase ground fault

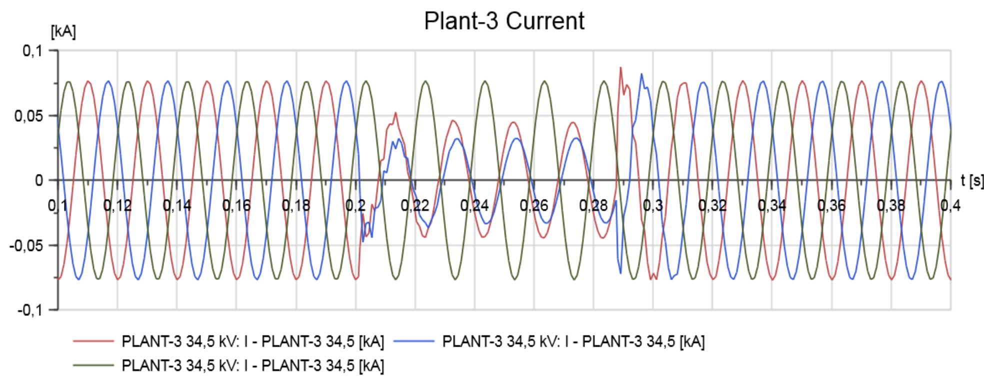


Figure 6.37 Plant-3 curret levels at phase to phase ground fault

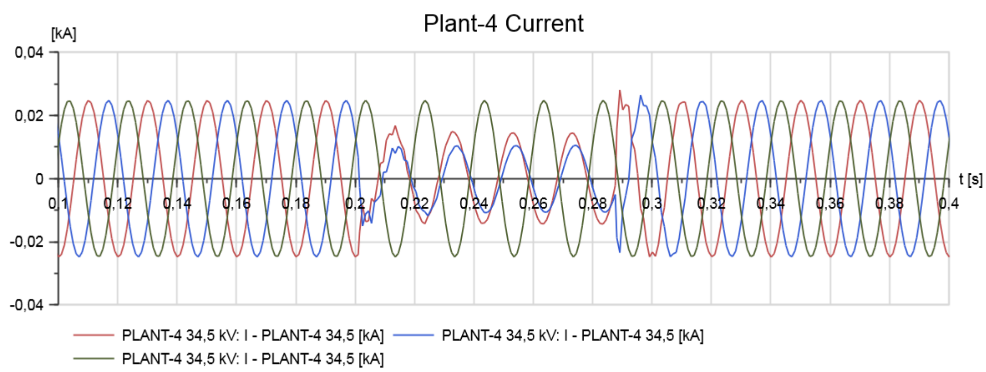


Figure 6.38 Plant-4 curret levels at phase to phase ground fault

All plants were connected to the same bus. Therefore, there was no voltage level difference in the buses of each plant. All of the obtained current waveforms were the same shape as expected. Because all plants had different loads, they had different current level magnitude.

GT-1 and GT-2 Currents

GT-1 and GT-2 current waveform is shown in Figure 6.39 and 6.40.

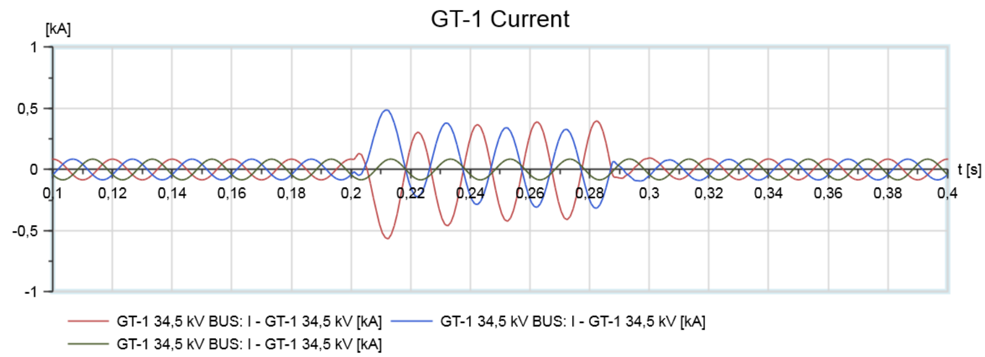


Figure 6.39 GT-1 curret levels at phase to phase ground fault

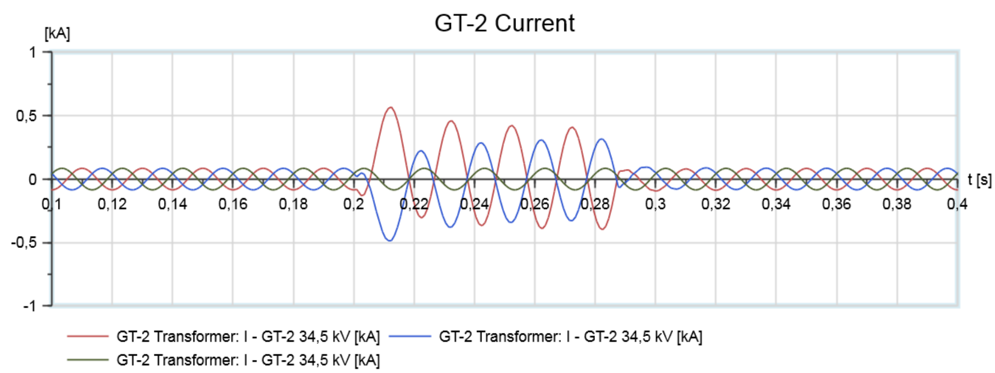


Figure 6.40 GT-2 curret levels at phase to phase ground fault

When the short circuit occurred, the currents of L1 and L2 phases sharply increased from nominal value to 5 times. The currents of L1 and L2 phases gradually decreased until the fault was cleared while L3 phase current value continued normally. Since GT-1 and GT-2 fed the fault from the opposite direction, there was a big increase in the fault currents in GT-1 and GT-2 as expected.

Plant-1, Plant-2, Plant-3, Plant-4 and GT-1 frequency deviations

The frequency deviations during the fault are shown in the graphs in Figure 6.41, 6.42, 6.43 and 6.44.

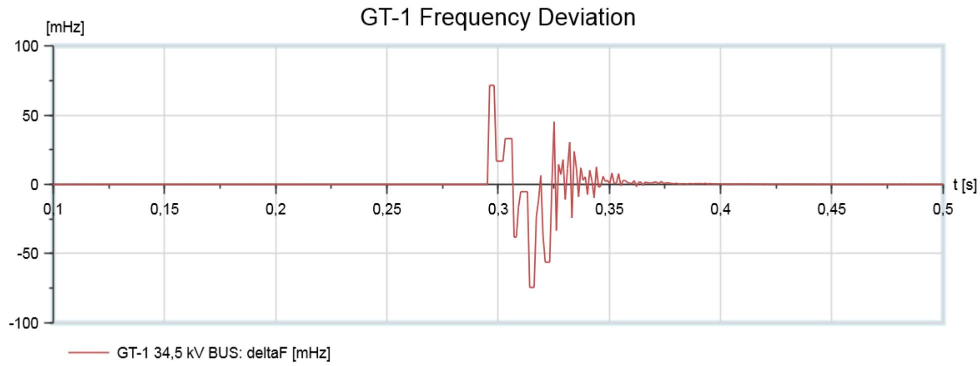


Figure 6.41 GT-1 Frequency deviation at phase to phase ground fault

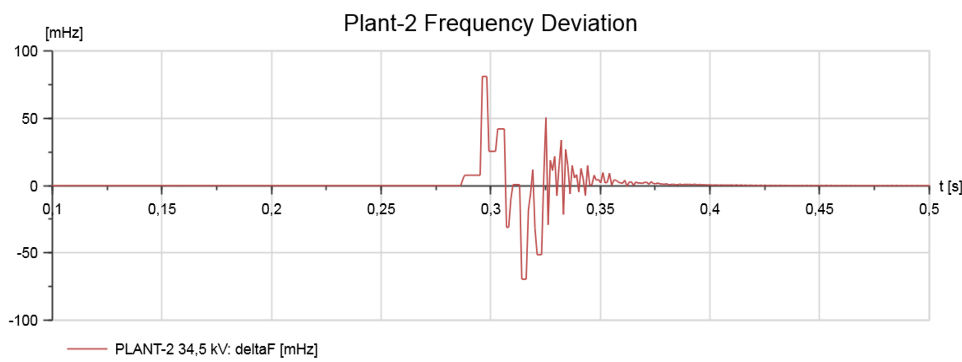


Figure 6.42 Plant-2 Frequency deviation at phase to phase ground fault

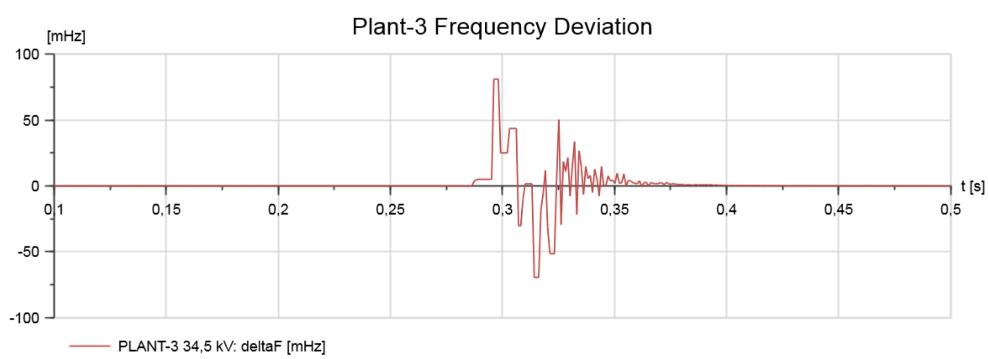


Figure 6.43 Plant-3 Frequency deviation at phase to phase ground fault

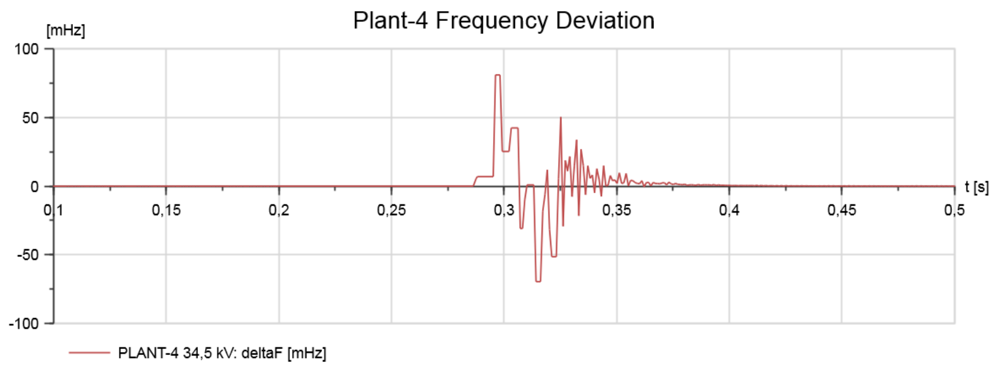


Figure 6.44 Plant-4 Frequency deviation at phase to phase ground fault

When the short circuit occurred, there was no deviation in all of the buses. But after the fault had been cleared, the frequency deviation began to be seen.

The frequency deviation levels increased to about 80 mHz. And then they gradually decreased until the 400th msec. The system became steady-state at the 400th msec. All plants and generation units were connected to the same bus so all frequency deviation was the same shaped as expected.

The fault was simulated by the simulation software as it was expected.

6.1.3 **Case 3 – The low voltage load three phase ground fault**

For the third case, the system is set up during low voltage fault. The three-phase ground fault circuit occurs at the plant-3 low voltage line low voltage load between the low voltage bus at the 200th msec, and then fault has been cleared at the 280th msec. The power system network configuration is shown in Figure 6.45.

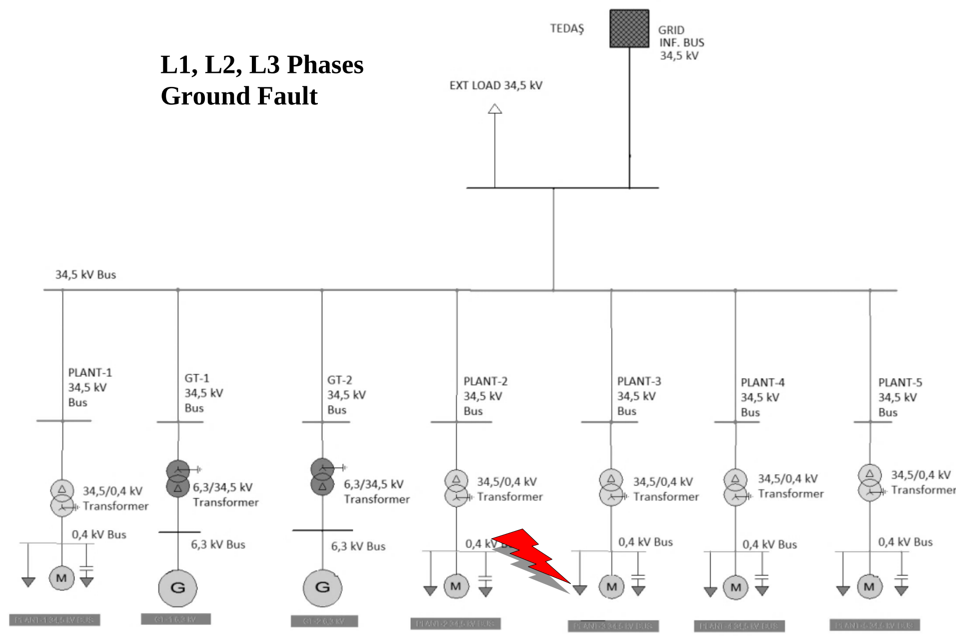


Figure 6.45 PSS/Sincal print screen single line diagram for low voltage three phase ground fault

At the 200th msec after simulation system started, the three phases ground short circuit occurred in load line of plant-3 low voltage side and at the 280th msec, the short circuit was cleared. The simulation lasted for 5 sec but all figures were shown between 0,1 sec and 0,4 sec for more details.

The voltage and current variations measured from the buses and the lines according to the time, when the short circuit at grid occurred, have been shown at below figures.

Grid Bus Voltage

It can be seen that there are voltage levels related to the fault in Figure 6.46.

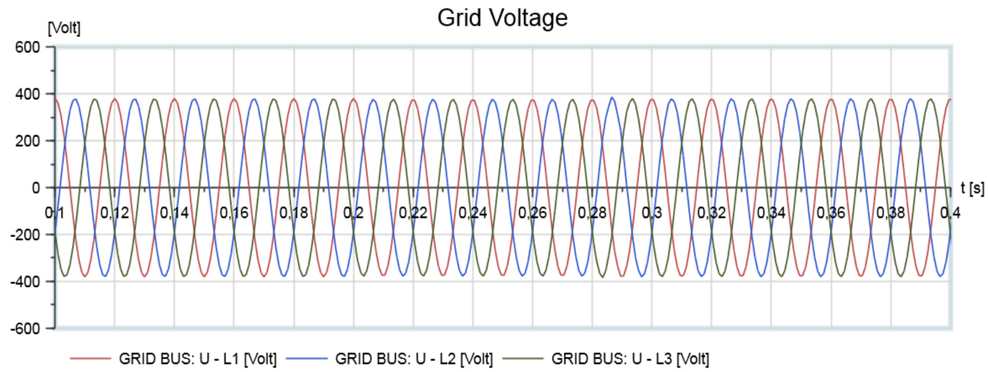


Figure 6.46 Grid voltage levels at low voltage load three-phase ground fault

When the short circuit in the fault location, the grid bus voltage level deviation was at nearly negligible value. The grid bus continued on steady-state situation. After the fault had been cleared, the grid bus voltage level deviation was at nearly negligible value, too. The grid bus voltages continued on steady-state.

Grid Connection Line Current

The current level during three phases ground fault can be seen from graphs in Figure 6.47.

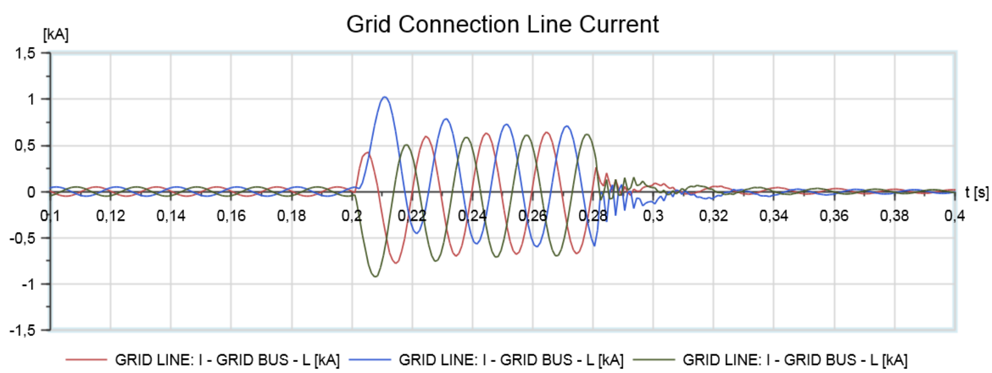


Figure 6.47 Grid connection line current levels at low voltage load three phase ground fault

GT-1, GT-2 and the grid fed the fault at the same time. Therefore, when the short circuit occurred, the currents of L1, L2 and L3 phases sharply increased from nominal values to 8 times. The currents of L1, L2 and L3 phases gradually decreased until the fault was cleared.

After the 280th msec, currents decreased fast to the magnitude about nominal levels. The system became steady-state at the 330th msec. This means; 50 msec later after the fault was cleared, the system became steady-state. There was no change in the angles of phases as expected.

Plant-1, Plant-2, Plant-3, Plant-4, GT-1 and GT-2 34,5 kV Bus Voltages

Figure 6.48, 6.49, 6.50, 6.51, 6.52 and 6.53 voltage levels during three phases ground fault can be seen in graphs.

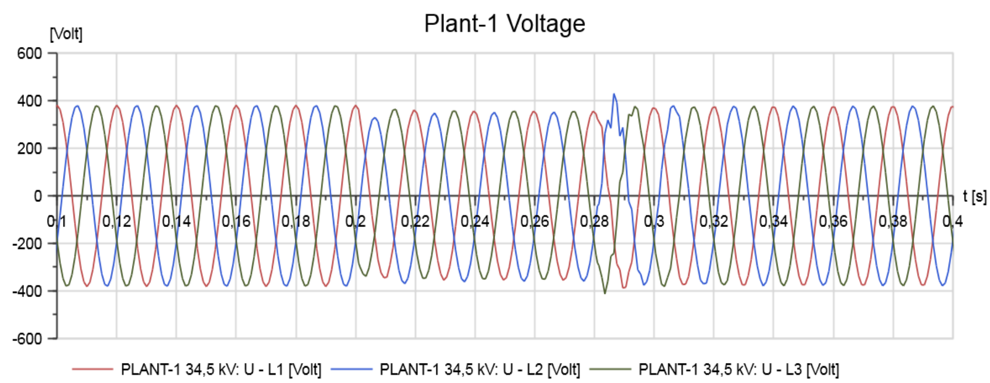


Figure 6.48 Plant-1 voltage levels at low voltage load three phase ground fault

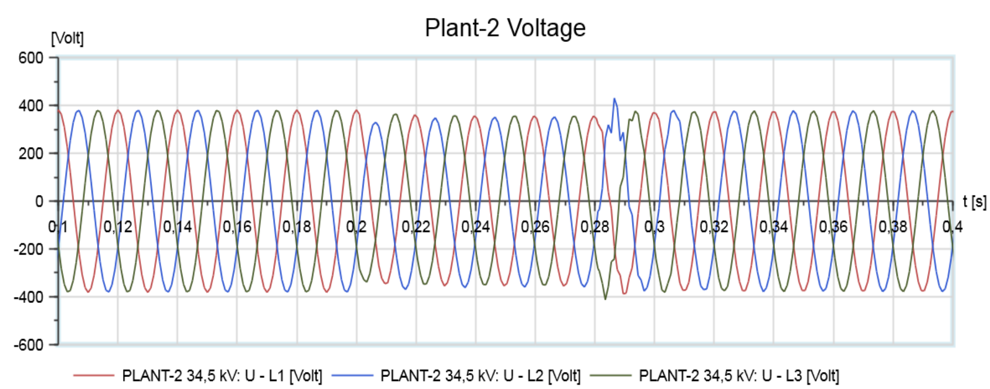


Figure 6.49 Plant-2 voltage levels at low voltage load three phase ground fault

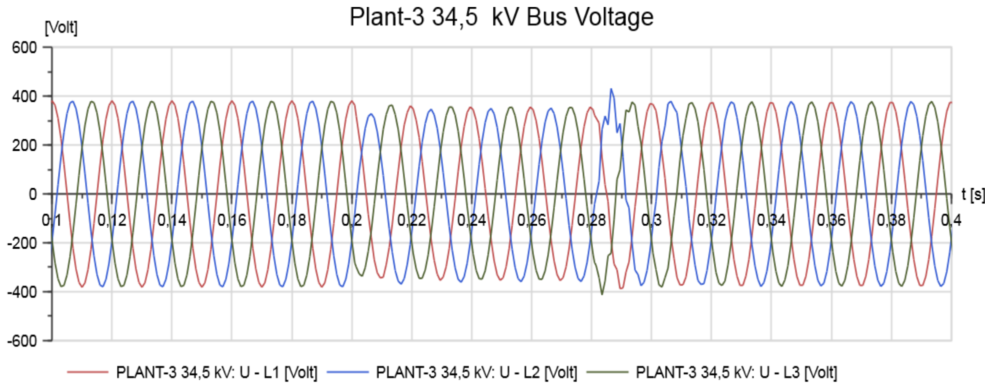


Figure 6.50 Plant-3 voltage levels at low voltage load three phase ground fault

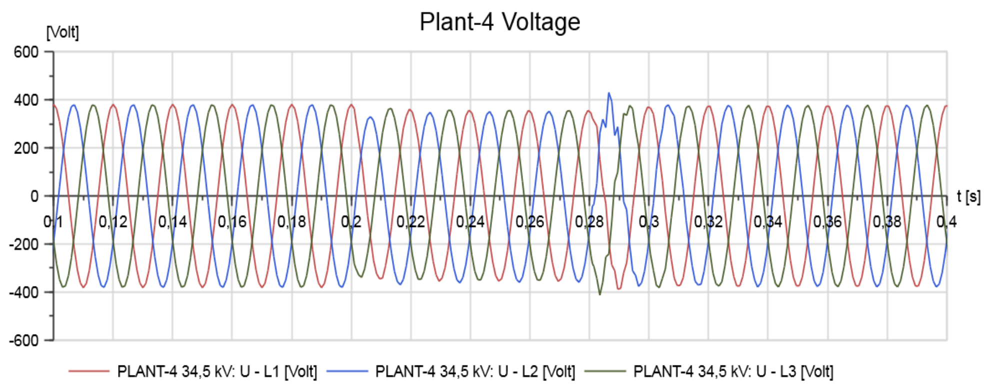


Figure 6.51 Plant-4 voltage levels at low voltage load three phase ground fault

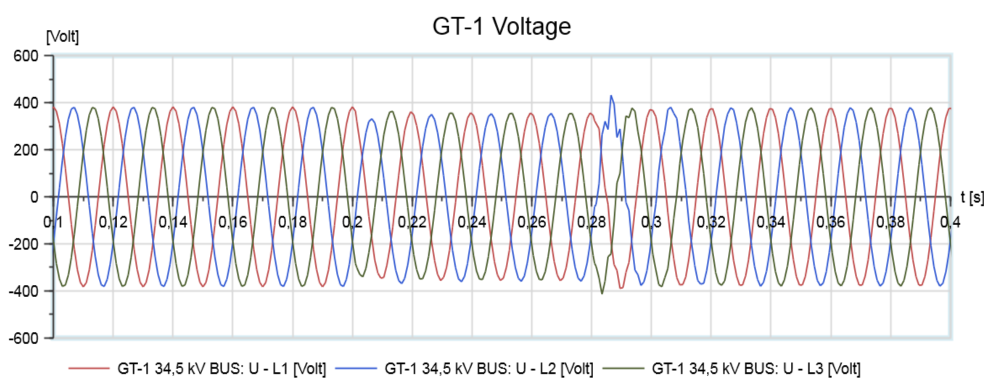


Figure 6.52 GT-1 voltage levels at low voltage load three phase ground fault

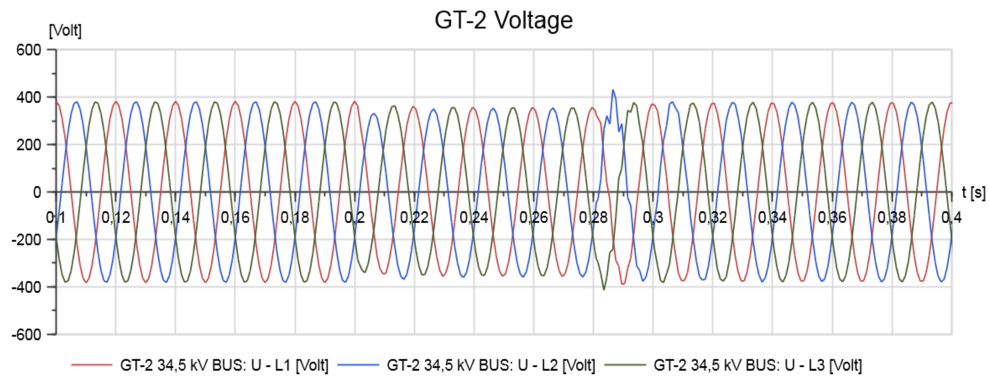


Figure 6.53 GT-2 voltage levels at low voltage load three phase ground fault

The voltages of L1, L2 and L3 phases dropped to about 375 volt value. This falling was at negligible value because the DG sources (GT-1 and GT-2 generator) were very near 34,5 kV bus and they were also directly connected to 34,5 kV bus. For this reason, these buses were the same voltage levels as expected.

Plant-3 0,4 kV Bus Voltage

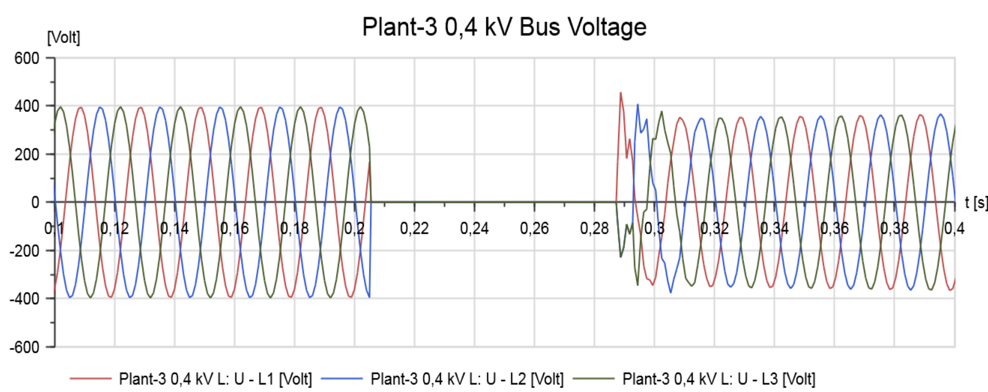


Figure 6.54 Plant-3 voltages levels at low voltage load three phase ground fault

After the three phases short circuit had occurred, the voltages of L1, L2 and L3 phases sharply dropped to zero volt value. The fault was cleared at the 280th msec but 30 msec after that, the system became steady-state.

Plant-1, Plant-2 and Plant-4 Currents

The current levels during the fault can be seen as in Figure 6.55, 6.56 and 6.56.

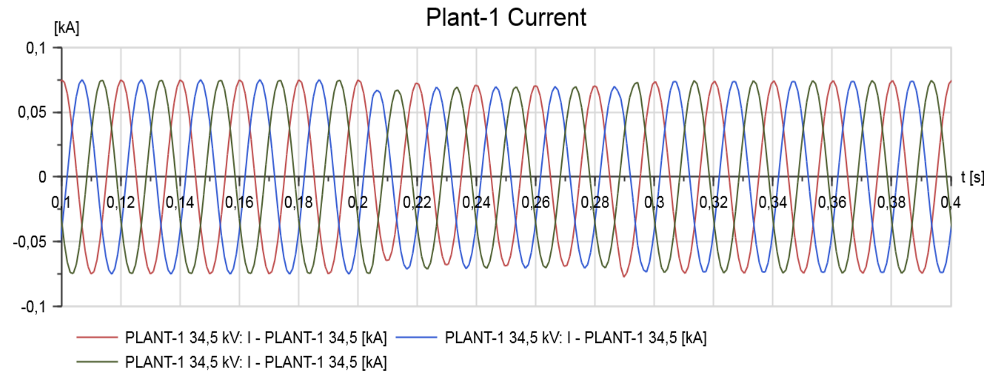


Figure 6.55 Plant-1 current levels at low voltage load three phase ground fault

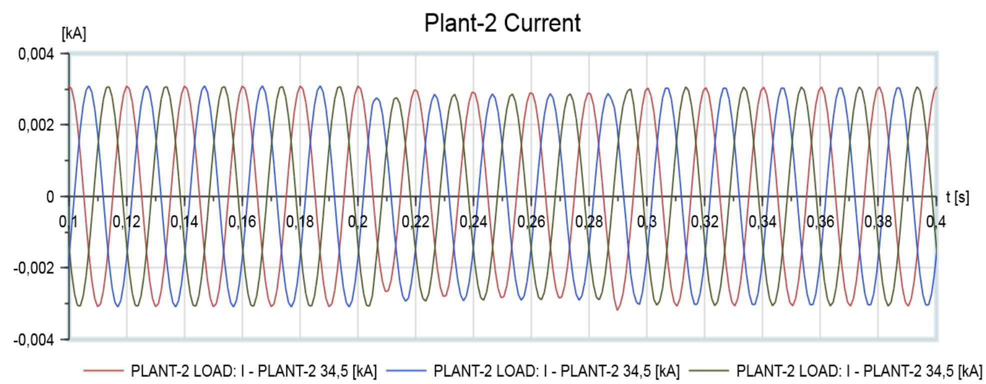


Figure 6.56 Plant-2 current levels atlow voltage load three phase ground fault

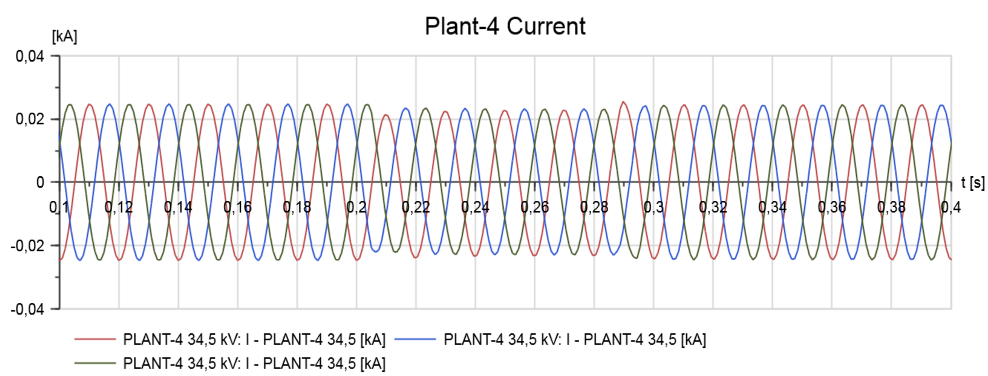


Figure 6.57 Plant-4 current levels atlow voltage load three phase ground fault

All plants were connected to the same bus so there was no voltage level difference in the buses of each plant. All of the obtained current waveforms were the same shape as expected. When the voltages dropped, the currents decreased. Because all plants had different loads, they had different current level magnitude.

Plant-3 34,5 kV and 0,4 kV Bus Currents

The current levels during the fault can be seen as in Figure 6.58 and 6.59.

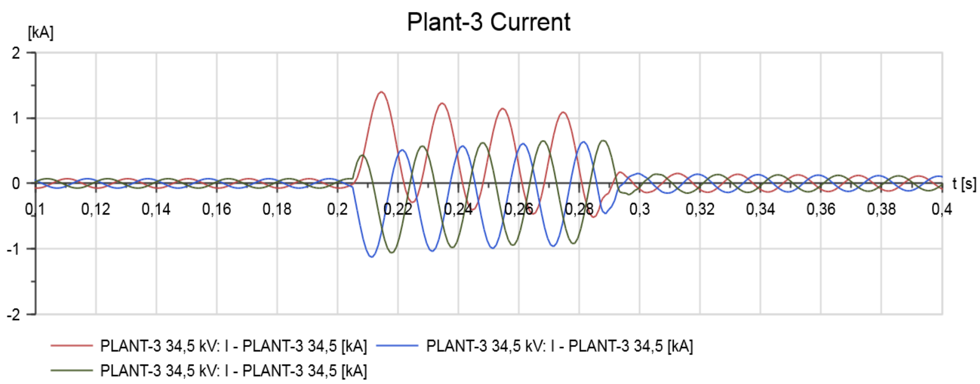


Figure 6.58 Plant-3 34,5 kV bus current levels atlow voltage load three phase ground fault

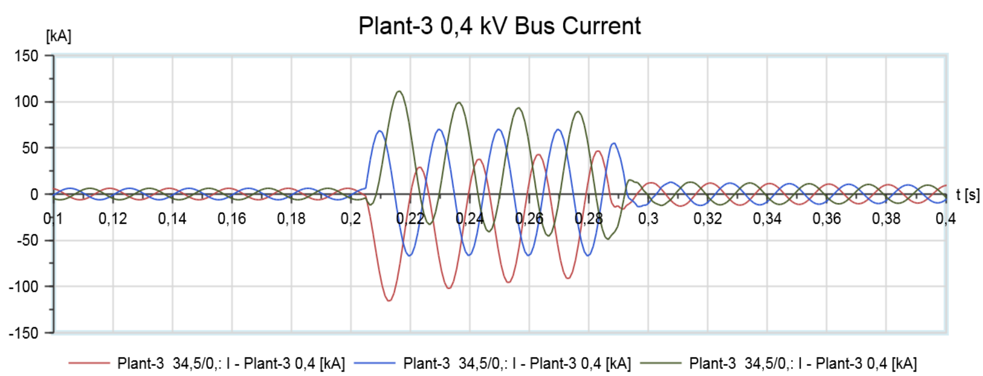


Figure 6.59 Plant-3 0,4 kV bus current levels atlow voltage load three phase ground fault

The grid and the generator units (GT-1 and GT-2) fed the short circuit fault. Therefore, when the short circuit occurred, the currents of L1,L2 and L3 phases sharply increased from nominal value to 12 times in 0,4 kV low voltage bus.

The currents of L1, L2 and L3 phases gradually decreased until the fault was cleared. After the 280th msec, the currents decreased fast to the magnitude about nominal level. The system became steady-state at the 330th msec. This means; 50 msec later after the fault was cleared, the system became steady-state.

Because GT-1, GT-2 and the grid fed the fault, there was a great increase in the fault currents in low voltage load. It did not change the angle between the phases. The system became steady-state at the 300th msec. This means; 20 msec later after the fault was cleared, the system became steady-state. This period was shorter than the 34,5 kV bus voltage level fault for becoming steady-state.

GT-1 and GT-2 34,5 kV Bus Currents

The current levels during the fault can be seen as in Figure 6.60 and 6.61.

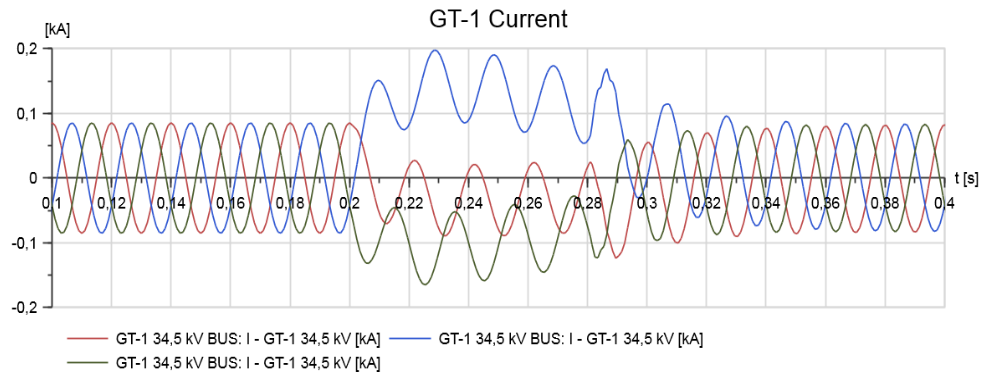


Figure 6.60 GT-1 34,5 kV bus current levels atlow voltage load three phase ground fault

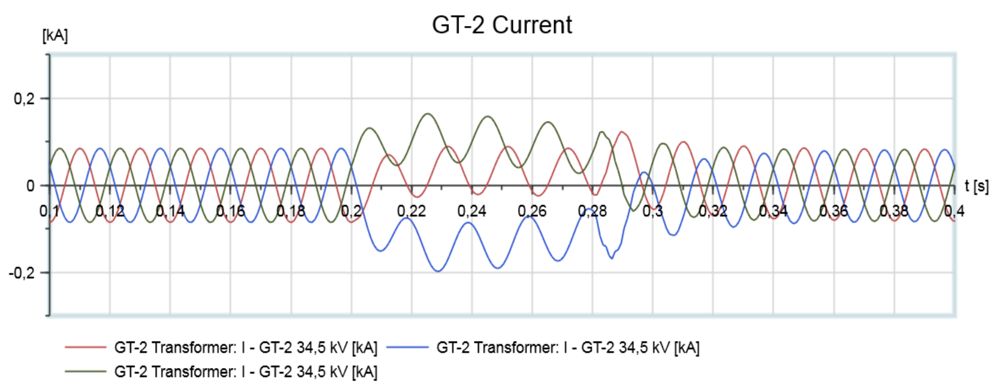


Figure 6.61 GT-2 34,5 kV bus current levels atlow voltage load three phase ground fault

There was some increase in the currents of GT-1 and GT-2 during the fault. When the short circuit occurred, the currents of L1, L2 and L3 phases sharply increased from nominal value to 2 times. The currents of L1, L2 and L3 phases gradually decreased until the fault was cleared. After the 280th msec, the currents decreased fast to the magnitude about nominal level. The system became steady-state at the 33o msec. This means; 50 msec later after the fault was cleared, the system was became steady-state. In Addition to GT-1 and GT-2, the grid also fed the fault.

Plant-1, Plant-2, Plant-3, Plant-4, GT-1 and GT-2 frequency deviations

The frequency deviation during the fault can be seen in Figure 6.62, 6.63, 6.64, 6.65, 6.66 and 6.67.

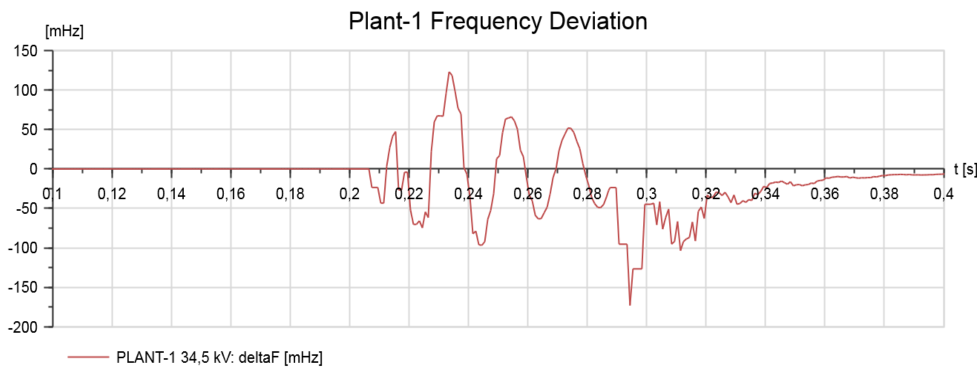


Figure 6.62 Plant-1 frequency deviation at low voltage load three phase ground fault

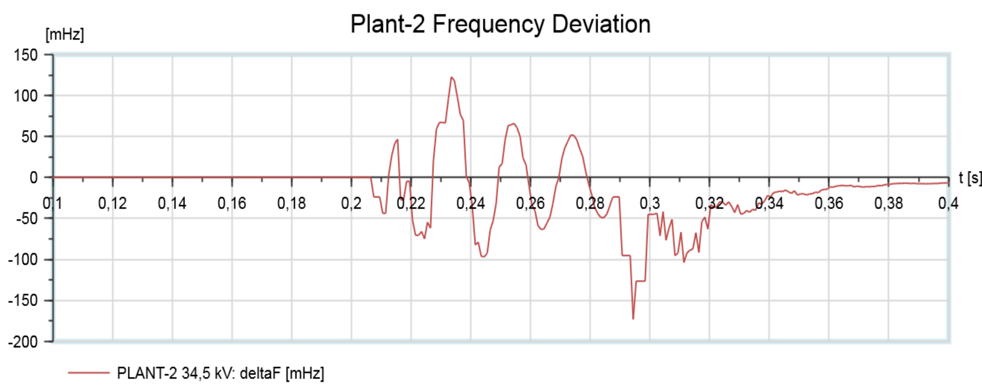


Figure 6.63 Plant-2 frequency deviation at low voltage load three phase ground fault

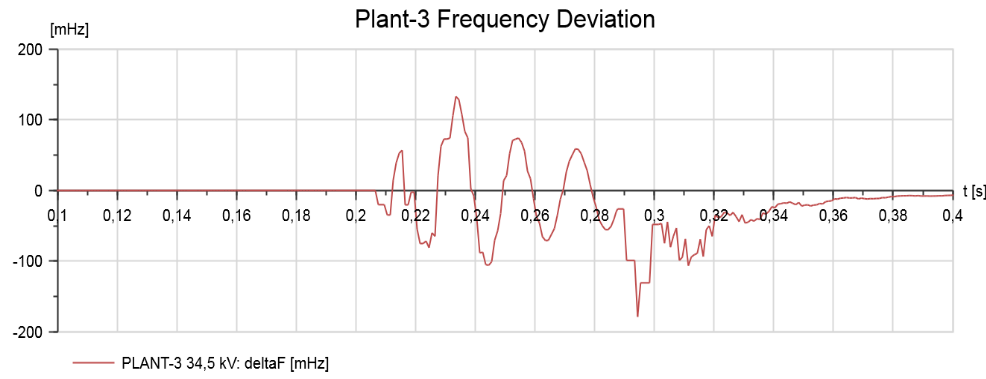


Figure 6.64 Plant-3 frequency deviation at low voltage load three phase ground fault

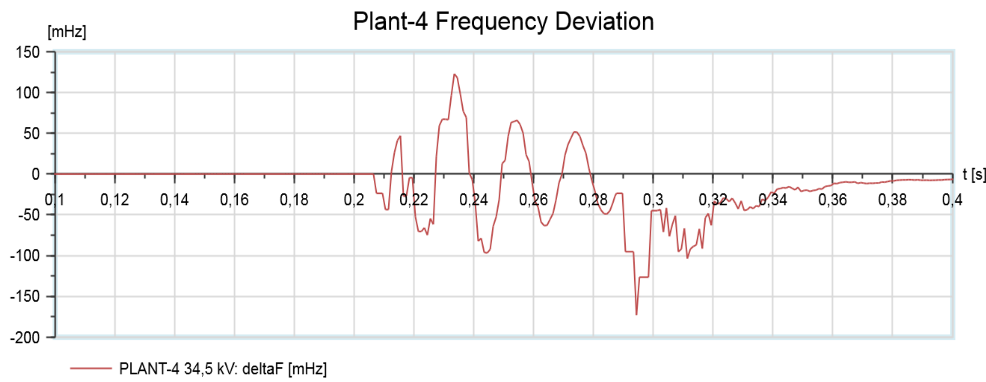


Figure 6.65 Plant-4 frequency deviation at low voltage load three phase ground fault

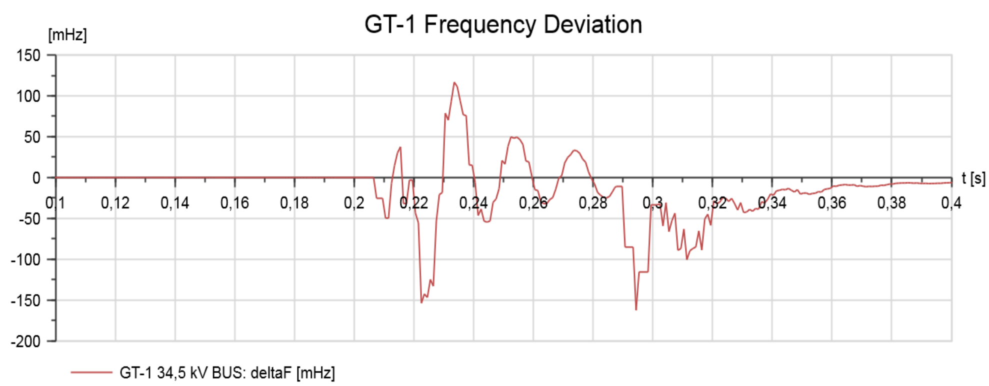


Figure 6.66 GT-1 frequency deviation at low voltage load three phase ground fault

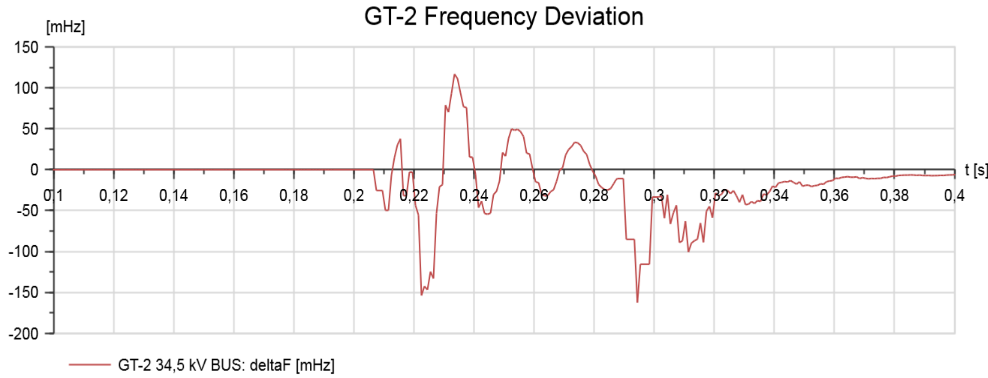


Figure 6.67 GT-2 frequency deviation at low voltage load three phase ground fault

The frequency deviation levels reached about 160 mHz in GT-1 and GT-2. At the same time, the frequency deviation increased to 180 mHz in Plant-1, Plant-2, Plant-3 and Plant-4. Although all waveforms were similar, the magnitude of the frequency deviation of GT-1 and GT-2 were different as expected.

The fault has been simulated by the simulation software as it was expected.

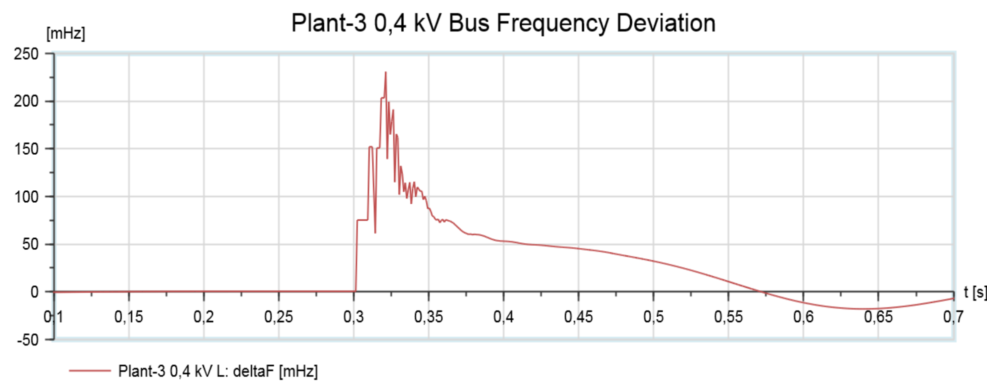


Figure 6.68 Plant-3 0,4 kV bus frequency deviation at low voltage load three phase ground fault

The biggest frequency deviation occurred in 0.4 kV bus where the fault location happened in above graph (Figure 6.68).

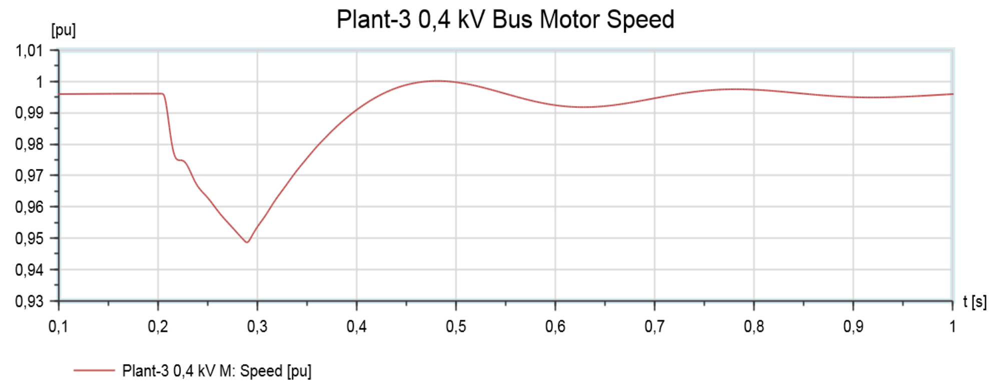


Figure 6.69 Plant-3 0,4 kV bus motor speed deviation

When the fault occurred, the speed of the motor began to decrease from nominal speed. After the fault had been cleared, motor speed increased until the 500th msec. The system became steady-state at the 1st sec.

6.1.4 Case 4 - phase to phase ground fault in island mode operation in plant-1

This case is very similar to Case-2. The differences are that the fault location is different and the system is working in island mode operation. The phase-to-phase ground fault circuit occurs at the distribution line between plant-1 34,5 kV bus and 34,5 kV common bus at the 200th msec and then the fault is cleared at the 280th msec.

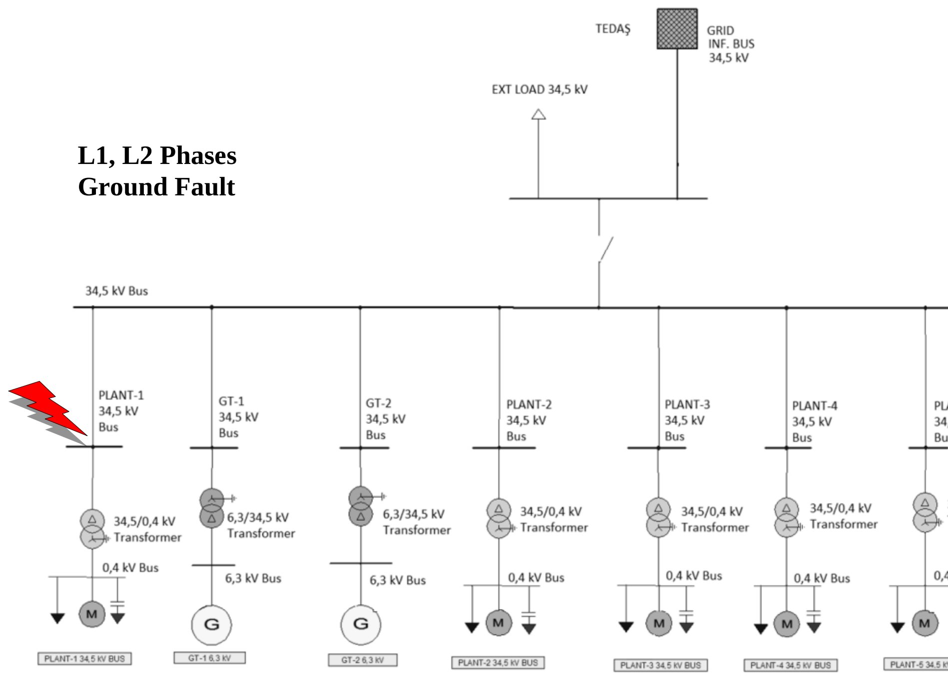


Figure 6.70 PSS/Sincal print screen single line diagram for phase to phase ground fault in island mode

The power system network configuration is shown in Figure 6.70. The phase to phase ground fault occurred at plant-1 34,5 kV bus in island mode operation of power plant at the 200th msec and then fault was cleared at the 280th msec. The simulation lasted for 5 sec. but all figures have been shown between 0,1 sec and 0,4 sec for more details.

The voltage and current variations measured from the buses and the lines according to the time, when a short circuit at the grid occurred, have been shown at below figures.

34,5 kV Bus, Plant-2, Plant-3 Plant-4, GT-1 and GT-2 Voltages,

The resultant waveforms for the phase-to-phase ground fault in island mode are shown in Figure 6.71, 6.72 6.73, 6.74, 6.75 and 6.76.

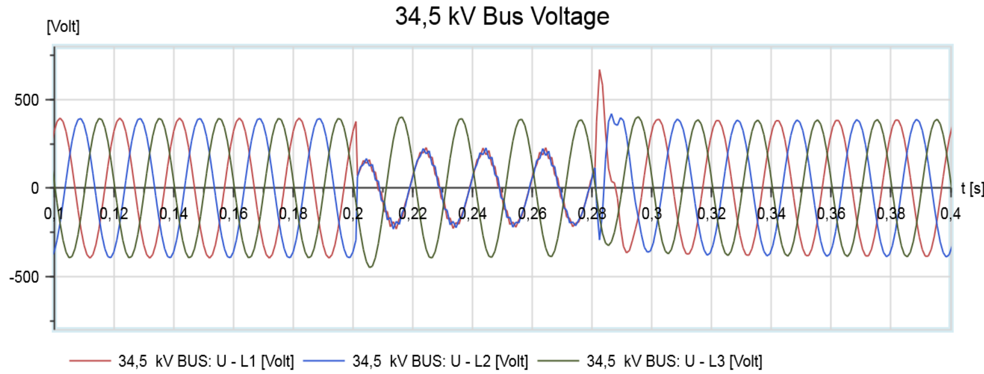


Figure 6.71 34,5 kV Bus voltage levels at phase to phase ground fault in island mode

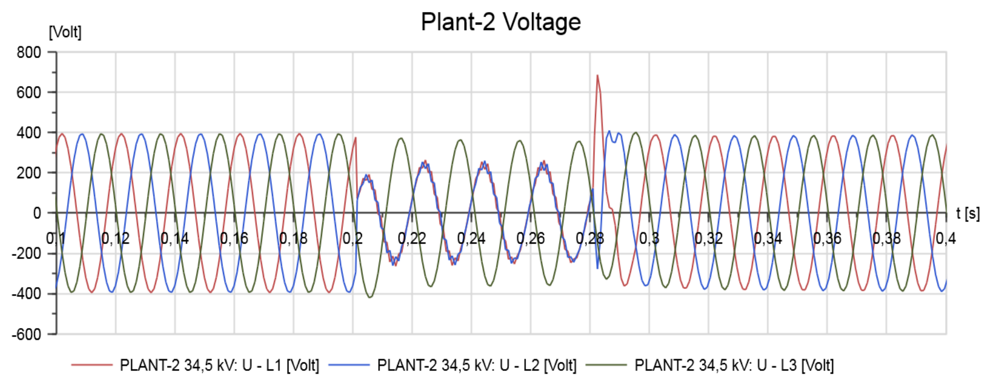


Figure 6.72 Plant-2 Bus voltage levels at phase to phase ground fault in island mode

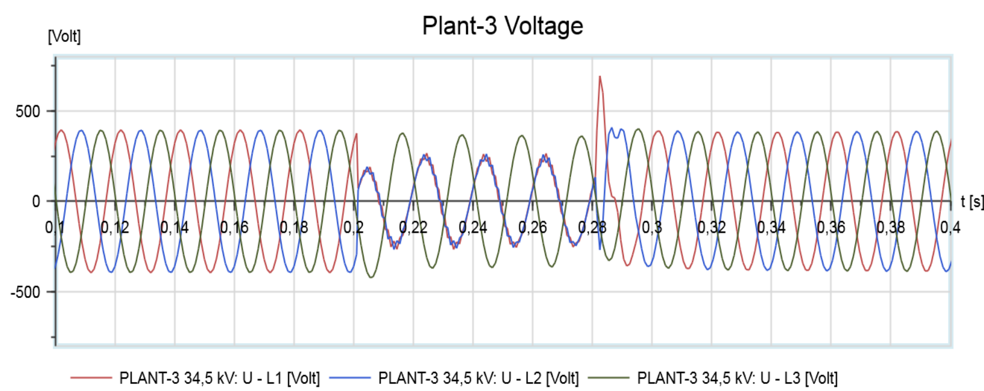


Figure 6.73 Plant-3 Bus voltage levels at phase to phase ground fault in island mode

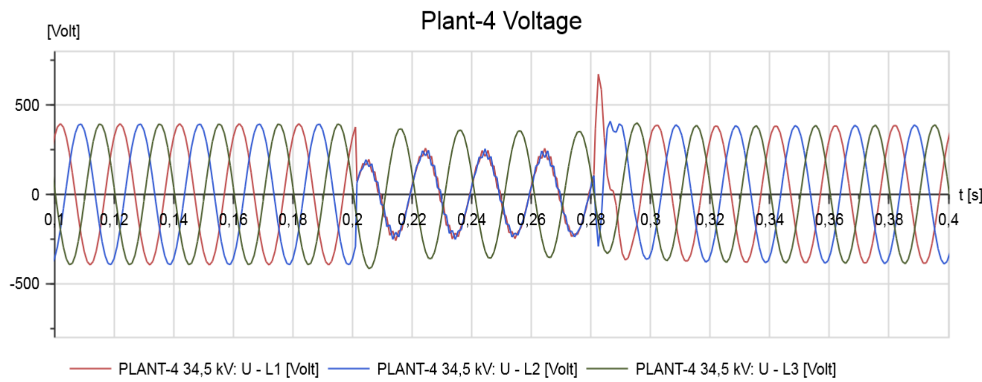


Figure 6.74 Plant-4 Bus voltage levels at phase to phase ground fault in island mode

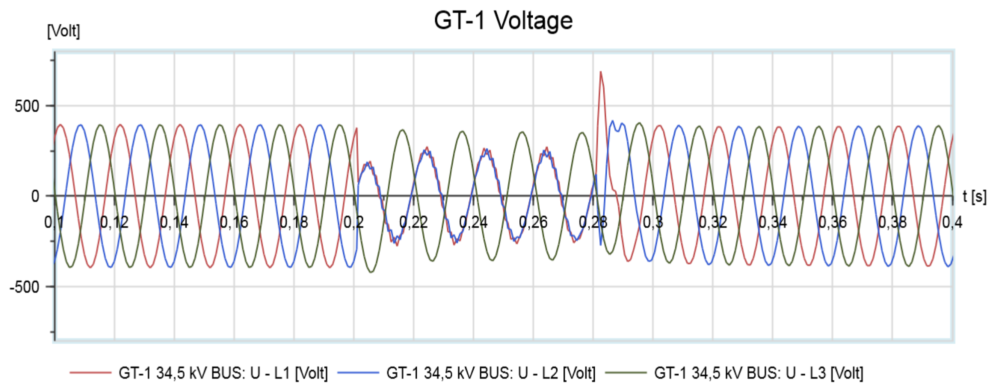


Figure 6.75 GT-1 voltage levels at phase to phase ground fault in island mode

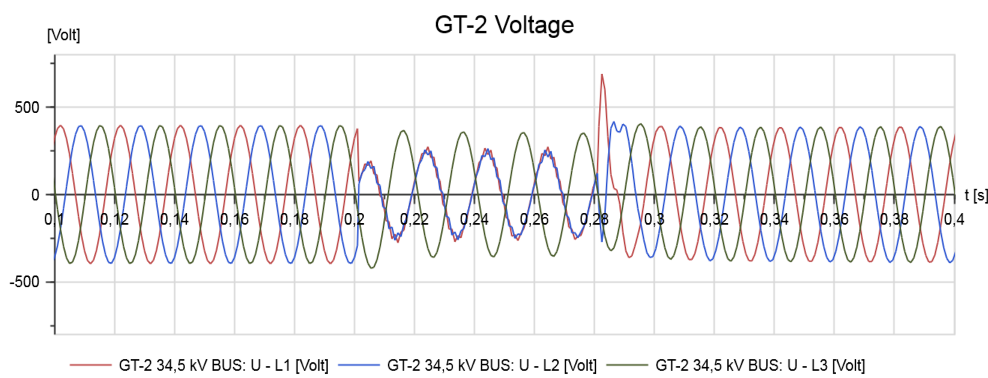


Figure 6.76 GT-2 voltage levels at phase to phase ground fault in island mode

The voltages of L1 and L2 phases dropped to about 200 volt value. The voltage levels were not zero. The DG sources (GT-1 and GT-2 generator) were very near 34,5 kV bus. There was no deviation voltage of L3 phase.

Plant-1 Bus Voltage

It can be seen that there are voltage levels about the fault in Figure 6.77.

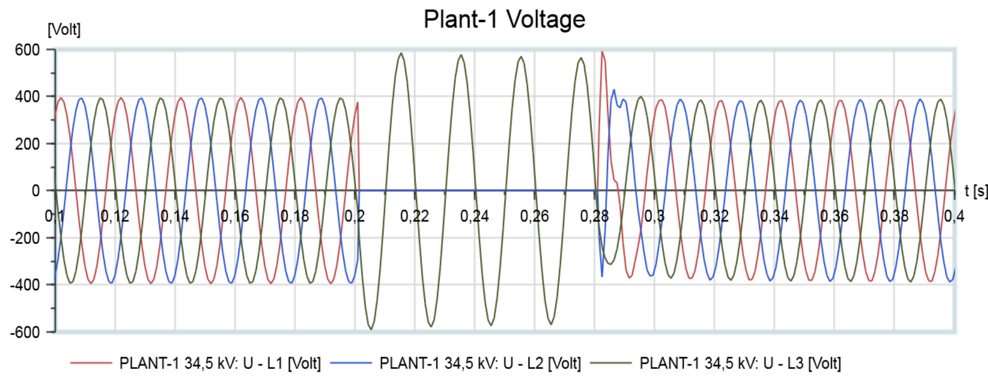


Figure 6.77 Plant-1 bus voltage levels at phase to phase ground fault in island mode

After the phase (L1) to phase (L2) short circuit had occurred, L1 and L2 phases voltage sharply dropped to zero volt value. At the same time, L3 phase voltage raised about 600 volt as expected and during the fault, L3 phase remained at fixed value of 600 volt. The fault was cleared at the 280th msec but 10 msec after the clearing, the system became steady-state.

Plant-1 Bus Current

Figure 6.78 currents level during phase to phases ground fault in island mode can be seen in graphs.

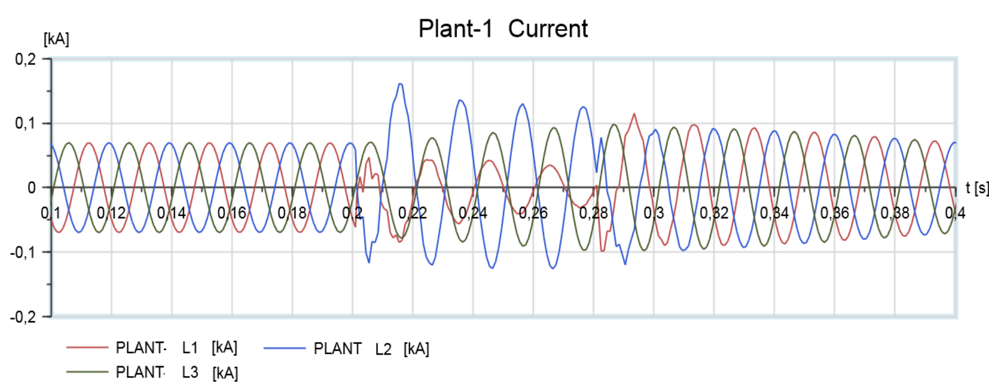


Figure 6.78 Plant-1 bus current levels at phase to phase ground fault in island mode

When the short circuit occurred, the currents of L1 and L2 phases sharply increased from nominal value to 2 times. The currents of L1 and L2 phases gradually decreased until the fault was cleared while L3 phase current value continued nearly normally. GT-1 and GT-2 fed the fault so there was a big increase in the fault currents in L1 and L2 phases as expected.

Plant-2, Plant-3 and Plant-4 Bus Currents

The current levels during the fault can be seen in below graphs (Figure 6.79, 6.80 and 6.81).

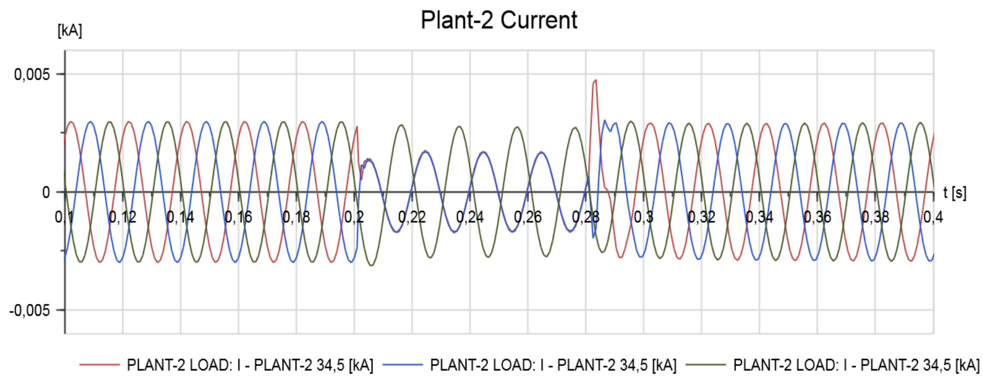


Figure 6.79 Plant-2 bus current levels at phase to phase ground fault in island mode

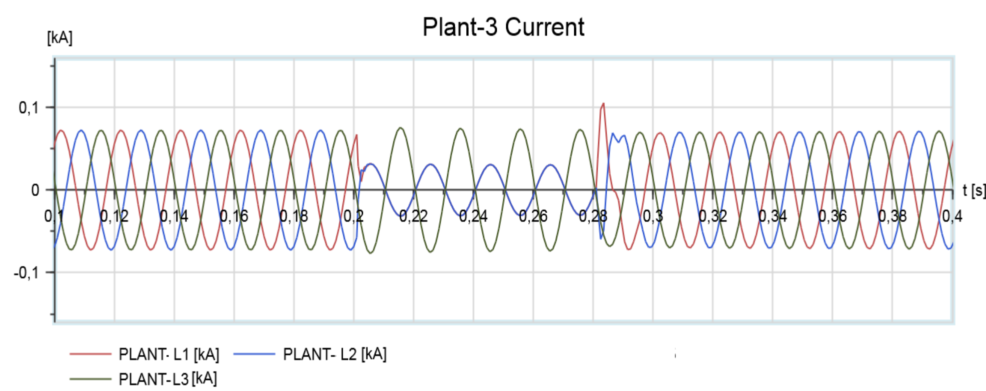


Figure 6.80 Plant-3 bus current levels at phase to phase ground fault in island mode

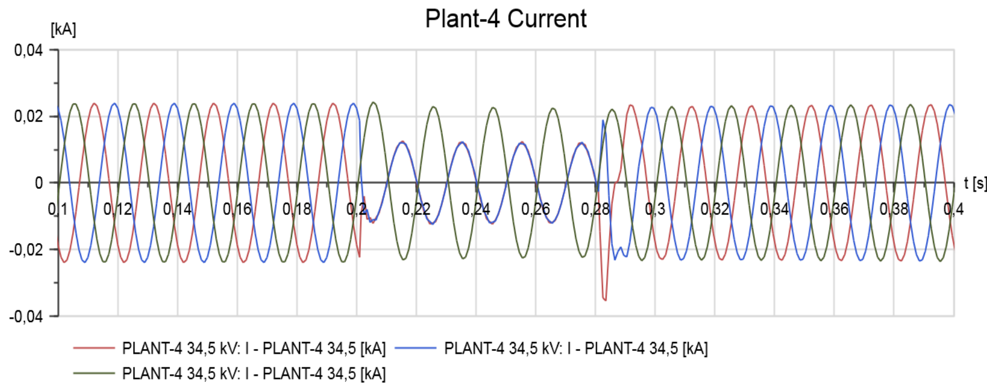


Figure 6.81 Plant-4 bus current levels at phase to phase ground fault in island mode

After the phase (L1) to phase (L2) short circuit had occurred, the currents of L1 and L2 phases dropped to half of the normal current value. After the fault, L1 and L2 phases continued on the same phase angle until the fault was cleared.

All plants were connected to the same bus. Therefore, there was no voltage level difference in the buses of each plant. All of the obtained current waveforms were the same shape as expected. Because all plants had different loads, they had different current level magnitude.

GT-1 and GT-2 Bus Currents

GT-1 and GT-2 current waveforms are shown in Figure 6.82 and 6.83.

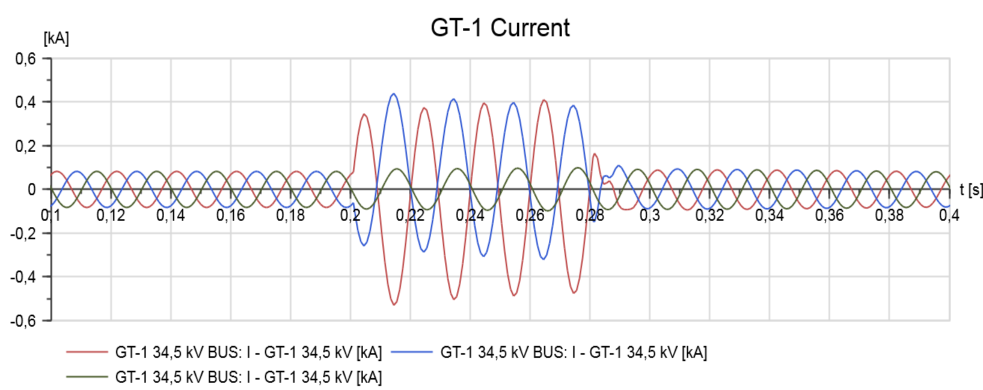


Figure 6.82 GT-1 bus current levels at phase to phase ground fault in island mode

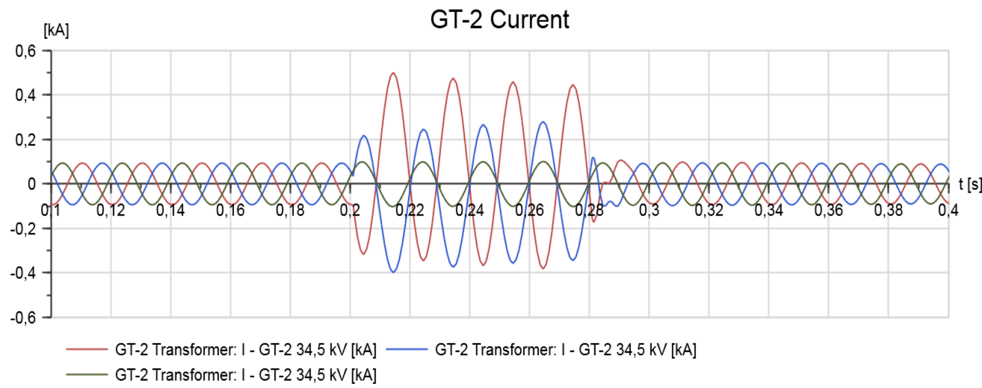


Figure 6.83 GT-2 bus current levels at phase to phase ground fault in island mode

As soon as the short circuit occurred, the currents of L1 and L2 phases sharply increased from nominal value to 5 times. The currents of L1 and L2 phases gradually decreased until the fault was cleared while L3 phase current value continued normally. Since GT-1 and GT-2 fed the fault direction, there was a big increase in the fault currents in GT-1 and GT-2 as expected.

After the beginning of the fault, L1 and L2 phases continued on the same phase angle until the fault was cleared.

6.2 Actual Fault Condition

At normal operation, with contribution from the 34,5 kV grid and from the generators GT-1 and GT-2, the three phases fault circuit occurs at the transmission line between grid and coupling bus at the 320th msec and then fault is cleared at the 370th msec. The power system network configuration is shown in Figure 6.84.

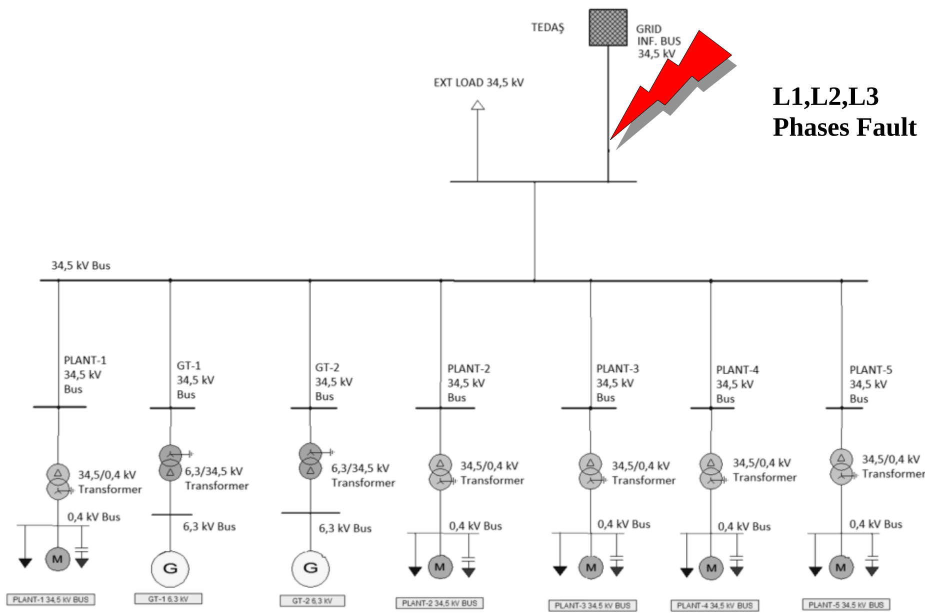


Figure 6.84 PSS/Sincal print screen- single line diagram of the industrial plant network

While the system was continuing on steady-state, the three phases short circuit occurred at the 320the msec and the short circuit was cleared at the 370th msec. The data of results have been shown according to the signal wave forms measured from the energy analyzers at each bus in Figure 6.85, 6.86, 6.87 and 6.88.

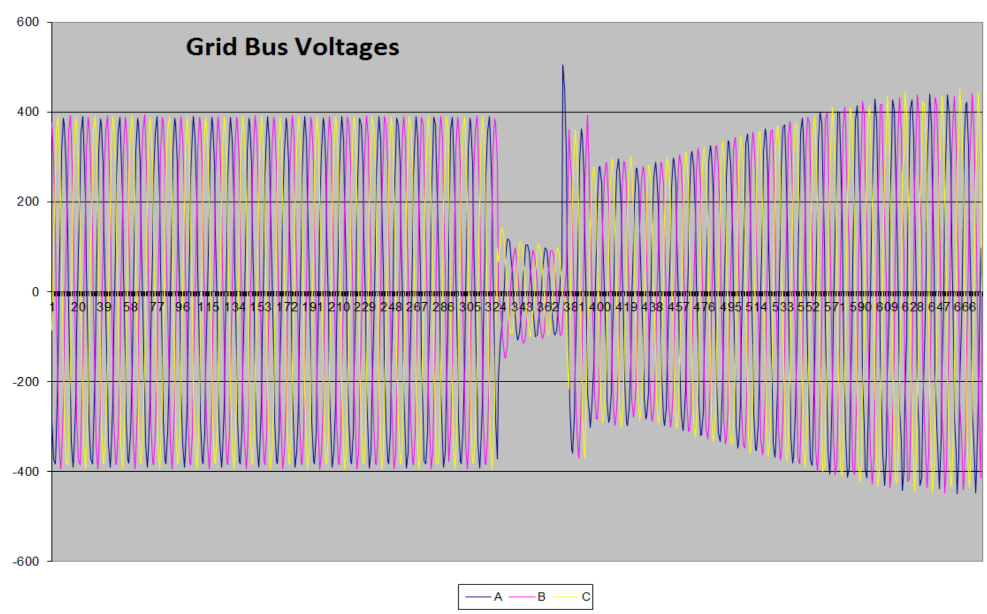


Figure 6.85 Grid voltage levels at three phases ground fault at actual condition

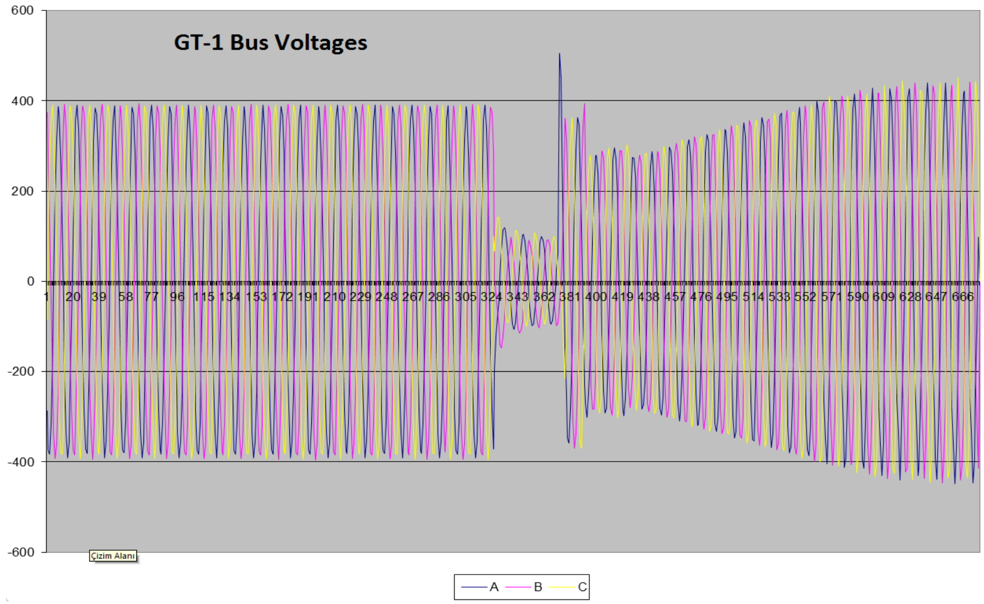


Figure 6.86 GT-1 voltage levels at three phases ground fault at actual condition

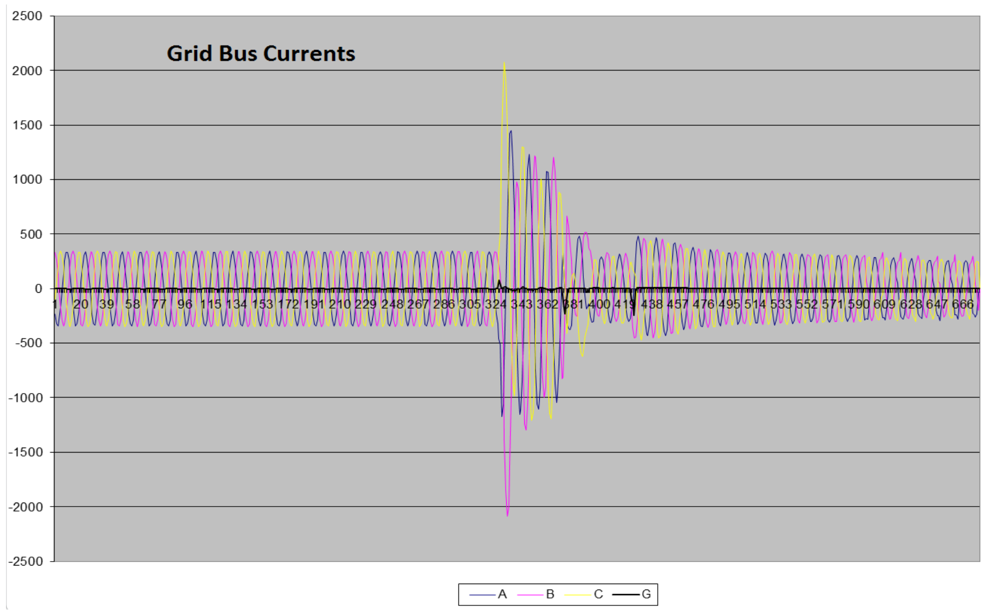


Figure 6.87 Grid currents levels at three phases ground fault at actual condition

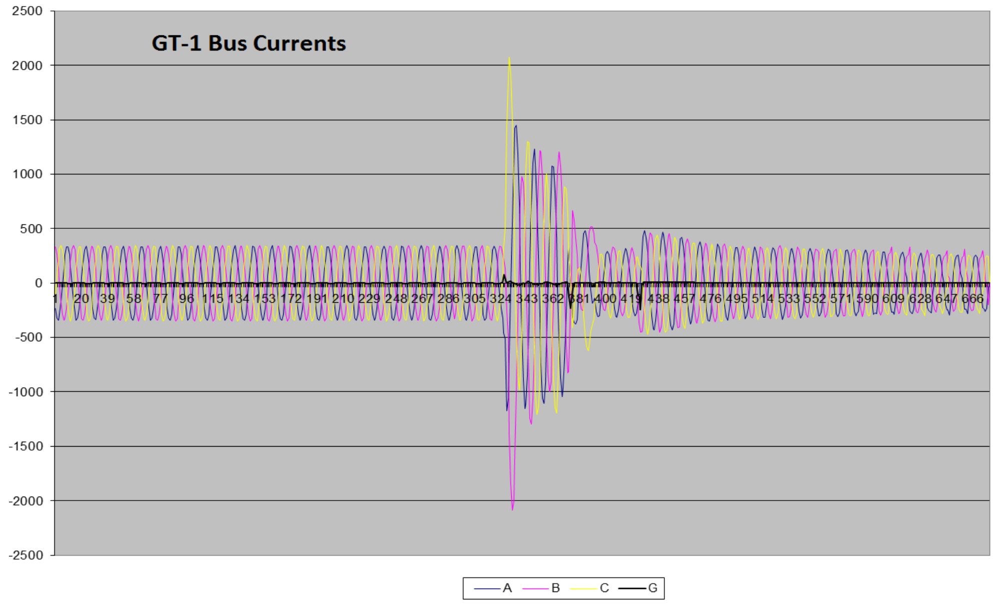


Figure 6.88 GT-1 currents levels at three phases ground fault at actual condition

After the three phases short circuit had occurred, the voltages of L1, L2 and L3 phases sharply dropped to about 110 volt value. Soon after the fault occurred, the currents of L1, L2 and L3 phases sharply increased from nominal value to 7 times. The currents of L1, L2 and L3 phases gradually decreased until the fault was cleared. After the 390th msec, the currents decreased fast to the magnitude about nominal level.

It was seen that there was a great increase in the fault current in the node grid connection line.

Because the exact fault location was not known, the magnitudes of the measured voltages and currents were different from the obtained simulation. The reason for this was that the loads and impedances changed momentary.

6.3 Comparison of Simulation Results of Cases

The table below has been formed with the findings, which were obtained from 4 different cases realised with simulation.

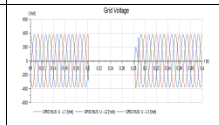
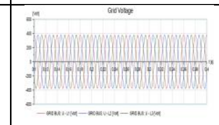
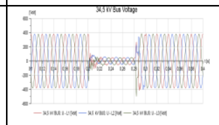
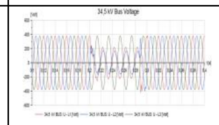
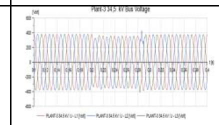
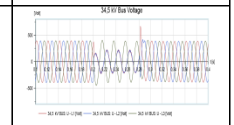
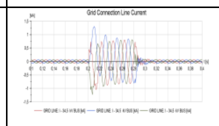
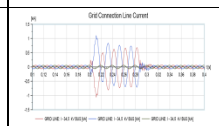
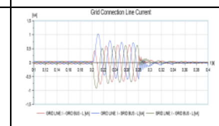
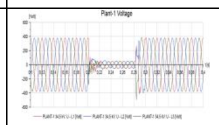
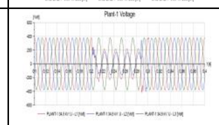
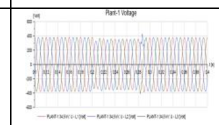
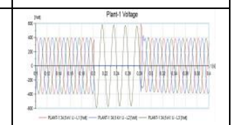
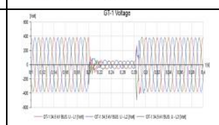
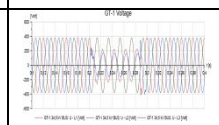
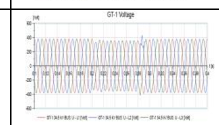
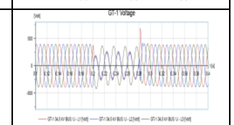
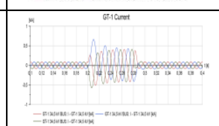
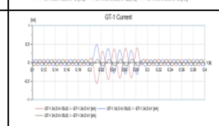
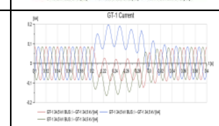
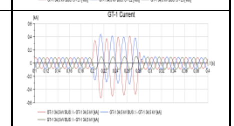
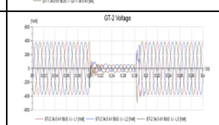
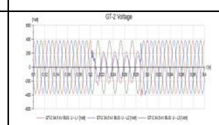
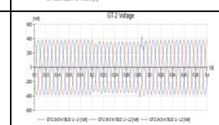
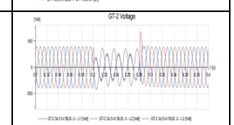
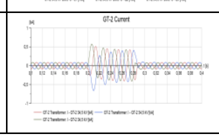
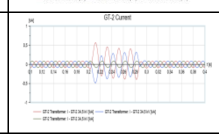
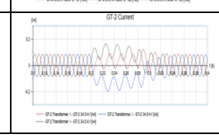
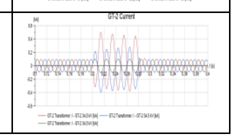
	Case-1	Case-2	Case-3	Case-4
Grid voltages				--------------
34,5 bus Voltages				
Grid Connection Line Currents				-------------
Plant-1 Voltages				
GT-1 Voltages				
GT-1 Currents				
GT-2 Voltages				
GT-2 Currents				

Table 6.1 Comparison of simulation results of cases

The table above has been formed with the findings which were obtained from 4 different cases realized with simulation. When the four different cases are compared;

When Case-1 and Case-2 are compared, it has been seen that the highest short circuit current has been three phases fault type.

When Case-1 and Case-3 are compared, it has been seen that the state which Case-1 affected the plant 1, 2, 4 and 5 more than the state which the Case-3 affected them

When all the cases are compared, the lowest fault current has occurred in the fault location which has occured at the low voltage side.

Because of the faults which have occurred at the low voltage sides, the voltages at the high voltage sides have not been too much affected but the great changes in the currents have occurred.

At the time the short circuits have occurred, it has been seen that the measured voltages which are nearer the fault location have been lower more than the further ones.

When Case-3 and Case-4 are compared, because the short circuit which has occurred in island mode operation was not supplied by the grid, the fault currents have occurred at lower level than the mode when the power plant has been connected to the grid.

CHAPTER 7

CONCLUSION

The analysis of the short circuit in the power system is one of the important terms for safety of the property, equipment, and human and also in proper sizing of the protection relays and conductor cross-section of the power transmission line selection. For this purpose, the power plant in three-phase power system with PSS/SINCAL has been studied for the short circuit analysis with the real line parameters.

The analysis of power systems is directed to the analysis by modeling the circuit elements in the computer system. The development of the simulation programs day by day, the modeling and the accuracy of the methods used improve the accuracy of the data obtained and the acquisition of result parameters. In the manual calculations in the short circuit event, the short-circuit pulse current is calculated with the help of coefficients which are obtained from short circuit event.

The short circuit analysis can be done with the PSS/SINCAL. In the PSS/SINCAL software, the generator, the transformer, the line, the load and the motor parameters such as complex circuit can be modeled in detail.

The simulation models are used as circuit blocks which are in their stamina and transferring the value to the computer. The collected basic parameters are re-elected according to the system eliminations and the program makes the situation a little more useful for the calculation needs. The whole power system of the industrial plant is modelled and the analysis is carried out on software. The simulations on modelled power system are practical ways to define the fault currents for a certain condition.

The most important part of the thesis presents the results showing the difference in magnitude of fault currents supplied at different fault locations. The faults have been simulated at four different cases and two operation modes to confirm the effect on the magnitude of the fault currents and voltages. The results show a difference between the fault currents supplied by only DG unit and the fault currents supplied by also the grid in addition to DG unit. The difference in the faults is much higher in the island mode operation faults than the faults in the grid.

The results obtained from after the actual fault are very similar to the results obtained by simulation.

In future, an extension for the current study will evaluate the feasibility to use a similar techniques in commercial distribution system protection design and also to create a program that will be use in the procedure explained on the usual short-circuit results to determine the maximum short circuit current.

CHAPTER 8

SUGGESTIONS

In this thesis, the short circuit faults are analyzed for the modelled power system during a severe fault on the grid, on the power plant and on the other connected plants.

In this research, the gas turbine model was only considered. The other models such as a fuel cell, a micro-turbine, and a solar cell also can be used in the distributed generation. These models should be considered to study the power system analysis of the issues on the distributed generation. Also, other power system issues like harmonic, power flow, dynamic analysis, voltage and angle stability analysis, protection device coordination and flicker can be analyzed.

Besides the operational solutions, the solutions based on equipment also may be investigated to enhance the protection technique and another area of research can be modelled for the distributed feeders with load and distributed generation.

BIBLIOGRAPHY

Adnan Kakilli, 2013, System Analysis with the MVA Method for Symmetrical Three-Phase Faults, TEM Journal – Volume 2, Number 1.

Ahnlund, J., 2014, Short-circuit Contributions from Fully-rated Converter Wind Turbines, Master Thessis,

Anderson, P. M., 1995, Analysis of Faulted Power Systems, IEEE Press Editorial Board.

Angelopoulos K., 2004, Integration of Distributed Generation in Low Voltage Networks: Power Quality and Economics, Master Thessis, University of Strathclyde in Glasgow, Department of Mechanical Engineering.

Ansuman Mohapatra, Basanta Kumar Panigrahi, 2014, Detailed Analysis of Grid Connected Distributed Generation Based Hybrid System Under Different Fault Conditions, 2014 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC).

Das, J. C., 2002, Power System Analysis Short-Circuit Load Flow and Harmonics, Marcel Dekker, Inc.

Das, R., 1998, determining the locations of faults In distribution systems, Master Thesis, Head of the Department of Electrical Engineering University of Saskatchewan.

El-Hawary, M. E., 2000, Electrical Energy Systems, CRC Press.

El-Khattam, W., Salama, M.M.A., 2004, Distributed Generation Technologies, Definitions and Benefits, Electric Power Systems Research, No:71.

Gakhar, P., Manglani, T., Doda D. K., 2013, Advancement & Role of DG Technology in Distribution System, International Journal of Recent Research and Review, No: 6.

BIBLIOGRAPHY (cont'd)

General Electric Company, 1989, Application Information Short- Circuit current Calculations,General Electric Company.

Gers, J. M., Holmes, E. J., 2004, Protection of Electricity Distribution Networks, The Institution of Engineering and Technology.

IGNOU, 2015, Introduction to Power Plants, Indira Gandhi National Open University Indira Gandhi National Open University Publishing, from http://www.ignou.ac.in/upload/Unit-1-58.pdf.

International Electrotechnical Commission, 2001, IEC 60909-0: Short-Circuit Currents In Three-Phase A.C systems - Part 0: Calculations of currents, IEC.

J. Faig, J. Melendez, S. Herraiz and J. Sánchez, 2010, Analysis of Faults in Power Distribution Systems With Distributed Generation, International Conference on Renewable Energies and Power Quality (ICREPQ'10) Granada (Spain).

Jeffrey M. Smith, 1996, Power Plant Engineering, Springer Science Business Media, Inc.

Jenkins, N., Ekanayake, J.B., Strbac, G., 2010, Distributed Generation, A Macmillan Company**.**

Jyotsna Sharma, Akhilesh Dobhal, 2014, Analysis and Simulation of Faults in Power Distribution Systems with Distributed Generation, International Journal of Engineering Research & Technology (IJERT) Vol. 3 Issue 9, September.

Kadam Sandeep Ratnadeep, Y.N.Bhosale, Shrihari Kulkarni, 2013**,** Fault Level Analysis of Power Distribution System, Energy Efficient Technologies for Sustainability (ICEETS), 2013 International Conference.

Ken Darrow, Rick Tidball, James Wang and Anne Hampson, 2015, Catalog of CHP Technologies, Section 2. Technology characterization – Reciprocating Internal Combustion Engines.

BIBLIOGRAPHY (cont'd)

Kersting, W. H., 2002, Distribution System Modeling and Analysis, CRC Press.

Khan, S., 2008, Industrial Power Systems, CRC Press.

Mehta, V. K., Mehta R., 2005, Principles of Power System, S. Chand.

Murthy, R., 2007, Power System Analysis, BS Publications.

Patel, M.R., 1999, Wind and Solar Power Systems, CRC Press.

Püttgen, H. B., Macgregor, P. R., Lambert, F. C., 2003, Distributed Generation.

Ramachandran, V. A., 2011 , Short Circuit Analysis and Circuit Breaker Interrupting Capability Validations For Industrial Power Plants, Master Thessis, The University Of Texas At Arlington.

Rebizant,W., Szafran, J., Wiszniewski, A., 2011, Digital Signal Processing in Power System Protection and Control, Springer Science Business Media, Inc.

Renuka Kamdar , Mukesh Kumar Kirar, Manoj Kumar, Ganga Agnihotri, 2013, Short Circuit Analysis of an Industrial Distribution System, Proc. of the Second Intl. Conf. on Advances in Computer, Electronics and Electrical Engineering - CEEE 201.3

Resource Dynamics Corporation, 2001, Assessment of Distributed Generation Technology Applications, Maine Public Utilities Commission.

Sallam, A.A., Malik, O.P., 2011, Electric Distribution Systems, IEEE Press Editorial Board.

Siemens, 2013, PSS/SINCAL Dynamics, Siemens PTI.

Tleis, N. D., 2008, Power Systems Modelling and Fault Analysis Theory and Practice, A Macmillan Company**.**

BIBLIOGRAPHY (cont'd)

Wikipedia 2015. 25.05.2015. https://en.wikipedia.org/wiki/File:Centralized_distributed.png

IGNOU, 2015, Introduction to Power Plants, Indira Gandhi National Open University Indira Gandhi National Open University Publishing, from http://www.ignou.ac.in/upload/Unit-1-58.pdf.