LOAD FLOW BASED ELECTRICAL SYSTEM DESIGN AND SHORT CIRCUIT ANALYSIS

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TABLE OF CONTENTS

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ABSTRACT

Load flow and short circuit behaviour of electrical energy systems are investigated. The system to be investigated, is designed based on a 230kVA power grid analytical model. Load flow analysis is crucial for the design of electrial power systems where tests related to load flow are indispensible. This work includes modelling of several electrical power components (transformer, power grid, bus bar, circuit breakers, etc.) to highlight the methods in the study of the system behaviour. Faults may occur in different scenarios, and all of the components have to be designed to withstand the worst case conditions based on the standards. Load flow and short circuit analysis are performed by variations of the load. Multiple design parameters are discussed and problems such as power factor correction, under voltages and over voltages are investigated.

Keywords: Load flow analysis; short circuit analysis; under voltage; over voltage, electrical equipment; power system behaviour

YÜK AKIŞ ANALİZİNE DAYALI ELEKTRİK SİSTEMİ TASARIMI ve KISA DEVRE ANALİZİ

ÖZET

Elektrik enerjisi dağıtım sistemlerindeki yük akış ve kısa devre davranışları incelenmiştir. İncelenecek sistem 230kVA güç şebekesi analitik modeline dayandırılarak tasarlanmıştır. Elektrik güç sistemlerinin tasarımında güç akışı analizleri çok önemlidir ve yük akışına ilişkin testler vazgeçilmez durumdadır. Bu çalışmada, sistem davranışını inceleme yöntemlerini vurgulamak için farklı elektrik güç bileşenleri (transformatör, güç şebekesi, bara, devre kesici vb.) de modellenmektedir. Farklı senaryolarda arızalar oluşabilir ve tüm bileşenler standartlarda tanımlanmış en kötü durum koşullarına bile dayanaklı olacak şekilde tasarlanmalıdır. Yük akış ve kısa devre analizleri yükün farklı seviyeleri için yapılmıştır. Farklı tasarım parametreleri ele alınmış ve güç faktörü düzeltme, yetersiz gerilim, aşırı gerilim gibi sorunlar incelenmiştir.

Anahtar Sözcükler: yük akış analizi; kısa devre analizi; yetersiz gerilim, aşırı gerilim; elektrik güç elemanları; güç sistemi davranışı

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LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS/ABBREVIATIONS

I_s	System current
Z_{sc}	Impedance of short circuit
ρ	Resistivity of resistance
R_c	Resistance of circuit
X_c	Impedance of circuit
θ_i	Intial temperature
θ_f	Final temperature
N_s	Synchronous speed
σ	Input for grid
α	Angle between impedence and resistance
VFD	Variable frequency drive
SSC	Short circuit calculation
RPM	Revolution per minute
EMF	Electro magnetic force
AC	Alternating current
RMF	Rotating magnetic field
MVAR	Mega volt ampere reactive
MW	Mega watt
OLTC	On Load tap changer
AVR	Automatic voltage regulator
kVA	Kilo volt ampere
RMS	Root mean square voltage
LG	Line to ground
LL	Line to line
LLG	Double line to ground
DB	Distributed panel
PF	Power factor
IEC	International electrotechnical commission

FEED	Front end engineering design
MCC	Motor control center

1. INTRODUCTION

Power transmission and distribution network is among the most important infrastructure components for a country's energy system. The prosperity of a country is heavily dependent on a flawless energy system. For a well functioning system, several analyses such as load flow and short circuit analysis are very useful to detect possible sources of faults. It is well known that faults have significant effects on the distribution systems of electrical energy (Bashir et al., 2010). Short circuit and load flow analysis are usually performed by different simulator programs (Prabhu et al., 2016). The main objective of the load flow solution in a distribution network is to evaluate the individual voltages of the phases in all buses attached to the grid corresponding to the specified system conditions. Since the active and reactive powers, the voltage and angles are included for each bus, four independent constraints are needed to solve for the four unknown parameters mentioned above (Patel et al., 2002). Each bus will have two unknown parameters (either the active and reactive powers in SWING mode or the voltage and the phase in the POWER FACTOR mode), and in our system (which will be examined later) there are eighten buses which means that thirty six variables exist in total. They include the active and reactive powers (represented by P and Q respectively), and by knowing these two factors one can calculate the current flowing into each branch which is also very important. As we are using the swing mode, voltage and angle values are given, hence, P and Q are the unknowns (Wadhwa, 2006).

Short circuit is one of the most crucial phenomenon in designing electrical systems which cannot be neglected in calculations. Equipments should be able to bear fault currents for a specific duration of time. Furthermore, protective equipments should manage to minimize the fault current itself. Short Circuit Calculation (SSC) is performed to find out the short circuit currents for designing, by these calculations one can see the withstand capacity of the system (Prabhu et al., 2016).

The main objective of this work is to give details about modeling electrical energy systems for load flow and short circuit analysis. Solutions for many hypothetical situations will be displayed: normal operation (in which power grid and the generator are working), maximum load operations (only some of the sources will work) and no load operation (circuit breakers are open) etc. Then, the analysis will investigate which precautions have to be taken in case of faults. The maximum and minimum fault currents of the system are calculated for the analysis and design of electrical equipments, and finally, faults including under voltages, over voltages are debugged and the problem of power factor correction is investigated.

2. BACKGROUND INFORMATION

The single line diagram (also called one line diagram) is an important drawing in power flow studies. This is the first step usually taken for understanding electrical systems. It plays a vital role in a variety of services including short circuit calculations, safety evaluation studies, load flow studies etc. It helps in troubleshooting and identifying fault locations. Electrical equipments are expressed as standardized schematic symbols. It is a kind of a block diagram which shows the power flow. Elements do not express the exact position or the size of the equipment but it is organized in a way that every equipment is in a branch of network. Each element used in the network has a different impedance.

2.1 Load Flow Analysis

The main purpose of the load flow analysis is to find the phase voltages at all buses connected to our system. The load-flow solution is an inevitable tool for power systems. As the active and reactive powers, voltage magnitudes and angles are involved for each bus, independent constraints are required to solve for the four unknown parameters (Kabir et al., 2014). There are many techniques to find a solution for the set of node voltage equations numerically, which are as follows:

- Gauss-Seidel
- Fast-Decouples
- Newton-Raphson

Newton-Raphson (NR) method is one of the best and widely used techniques for finding unknown parameters. In Newton-Raphson method, one of the generators is treated as a slack bus. A slack bus is also called an infinite bus because, theoretically, the generation capacity at this bus is very large. It is treated as the reference bus and with respect to it, the phase angles of the other bus voltages are calculated. The slack bus is kept out of calculation. It is due to the fact that the slack bus has to carry the entire loss of the system and the total loss cannot be calculated before the end of the iterations. (Kabir et al., 2014). The NR approach has many advantages over others, as it can be used for large networks requiring a smaller computer resource. This method is very sensitive on a good start, the use of a proper starting point significantly reduces the time of computation. It is not necessary to determine any high speed factor, the choice of loose bus is very important, and network editing requires less computing effort. The NR method is great and flexible, which allows it to be easily and efficiently deployed in a wide range of representation requirements, such as stage change and load change devices, regional exchange, active loads and remote voltage. NR based load flow analysis is the main step for sensitivity analysis, system state estimation, system optimization of laser network operating systems for many recently developed methods. NR is suitable for modeling, security evaluation and transmission stability analysis, and online computing (Stott, 1971). As the load in the power system is gradually increased, bus bar voltages slightly decrease until the slope of voltage-power curve goes to infinity. The Jacobian is usually descibed by a singularity in Newtron-Raphson method. In order to avoid the singularity related to the turning point, it is possible to choose different parameters for load and power at bus bars.

2.1.1 Newton-Raphson Load Flow in Distribution Networks

The distribution system is usually discussed with respect to the following features (Liu et al., 2002)(Bijwe and Kelapure, 2003):

1. Radical meshed topologies

   Most distribution systems are radical meshed because of the increasing requirement of demand load. Devices are connected mostly with many unessential interconnections between network nodes (Kersting, 1984).

2. Unbalanced operation

   Three phase unbalance conditions mostly cause a lot of complications and faults in the system so that phase quantities should be coupled (Das, 2006).

3. Loading Condition

   The Extreme Loading Condition (XLC) is usually described by an increasing load (according to a default pattern for both reactive and active power). Different types of load certainly have a big impact on the system, so, a properly calculated practical record is required for getting valuable results.

4. Dispersed Generation

   The installation of the existing generation in the current electrical system has a great impact on the planning and operation in real time. Many uncertainties show the power of the current generation to mobilize the generation, therefore, the generation of reproducers can be ignored in the performance of the energy system, so the operation and security are bad. The complexity of control, security, and maintenance of the energy distribution system are increased (Hadjsaid et al., 1999).

5. High R/X ratio of the distribution lines

   In distribution networks, both overhead lines and cables are used, R/X ratio is high ranging from 0.5 to 0.7. High voltage networks such as transmission networks have usually low R/X ratio because of the power losses. It plays a vital role to check the health and strength of the power grid i.e. whether it is weak or strong. A suitable system should be proposed to minimize the ratio for low voltages (Sarkar et al., 2016).

6. Non-Linear Model

   Non-linear loads such as rectifiers whose impedance changes with the change of voltages in the distribution system, cause fluctuations in the current to be drawn from system (Semlyen et al., 1991).

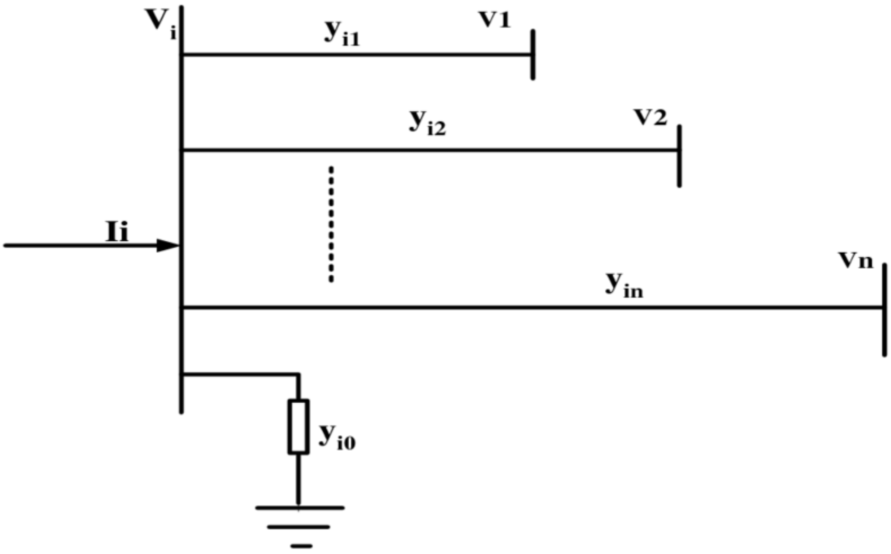


Figure 2.1 A typical bus of power system

With respect to Figure 2.1, power flow equations are derived in terms of the admittance matrix Y as follows:

$$I_i = \sum_{j=1}^{n} Y_(ij)V_j \tag{2.1}$$

where i, j denote the i^{th} and j^{th} bus respectively.

The equations can also be expressed in polar form:

$$I_i = \sum_{j=i}^{n} |V_{ij}||V_i| < \theta_{ij} + \delta_j \tag{2.2}$$

The current in terms of the active and the reactive power at the bus is given as:

$$I_i = \frac{P_i - jQ_i}{V_i} \tag{2.3}$$

By putting Eqn.(3) in Eqn.(2) one obtains:

$$P_i - jQ_i = |V_i| < -\sum_{j=i}^{n} |V_{ij}||V_i| < \theta_{ij} + \delta_j \tag{2.4}$$

By separating the real and imaginary parts we get:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||V_{ij}|cos(\theta_{ij} - \delta_i + \delta_j) \tag{2.5}$$

By using Taylor's series expansion about the initial estimate and by neglecting higher order terms, one may obtain the different roots as the solution.

2.2 Short Circuit Analysis

Short circuit analysis is used to determine the capacity of the system for producing short circuit current, electrodynamic withstand capacity of wiring and switchgear and comparing the magnitude of short circuit current with interrupting rating of over current protective (OCPD) (Fukunaga, 1994). As the interrupting ratings are defined in the standards, methods of conducting short circuit analysis are based on those standards. It causes severe hazard to power distribution system components. The main point in developing and applying protection system design is based on this analysis. Instruments that interrupt short circuit current are devices connected to the electric circuit to provide protection against excessive damages when short circuits occur. They stop the fault current by interrupting automatically without damaging the system mechanically, so short circuit calculations are needed for the protection of relays and for the rating of equipments (Sortomme et al., 2010).

Sizing of the electrical equipment is very important in every point while designing required equipments. Whatever type of short circuit happens (minimum or maximum), the protection instrument should be acting in the proper time.

The primary characteristics of short circuits are as follows:

- **Duration** (self-extinguishing, transient, and steady-state)
- **Location** (inside or outside of the electrical switchboard)
- **Phase-to-earth** (80 percent of faults)
- **Phase-to-phase** (15 percent of fault)
- **Three-phase** (only 5 percent of initial faults)

  The consequences of a short circuit usually depend on the type and duration of the fault, and on the place of the occurrence (near spark or arc places). Those faults may result in
- **Damage to insulation**
- **Welding of conductors**
- **Life hazards**
- **Heat effects such as the deformation of busbars, disconnection of cables**
- **Excessive temperature rise due to an increase in power losses**
- **Shutdown of a particular system**
- **Voltage drop during fault ranging from hundred to few in milliseconds.**

2.2.1 Development of the Short-Circuit Current

The model of a short circuit is based on a constant AC power source, a switch, an impedance Zsc that represents all the impedances upstream of the switch, and a load impedance Zs. In a real system, the source impedance is made up of different voltages (HV, LV) within a defined area A and length L.

When the switch is in service and there is no fault in the system, the system current I_s flows. When a fault occurs, very high short circuit current Isc will flow in the system due to a small impedance which is only controlled by the impedance Zsc. Short circuit currents produce a lot of heat into a system; they cause serious damage to the power distribution system. Hence, precautions have to be developed and applied for protection. So, circuit breakers or switchgears called interrupting devices are used which provide protection for the system against a severe damage (Disalvo and Campolo, 2009).

The current that will be produced during a sudden effect depends on the reactance X and the resistance R which makes the impedance Zsc:

$$Zsc = \sqrt{R^2 + X^2} \tag{2.6}$$

In power distribution networks, the reactance X = ω L is normally much greater than the resistance R and the R/X ratio is between 0.1 and 0.3. The ratio is virtually equal to cos α for low values:

$$cos\alpha = \frac{R}{\sqrt{R^2 + X^2}} \tag{2.7}$$

2.3 Protection Of A System

The bus and the switchgear/circuit breaker are important parts of the power system that are used to connect the flow of power and later isolate the device and the circuit if any fault occurs. The system includes the transformers, busbars, connectors, circuit breakers and the structure where it is installed. To isolate the faults in busbars all circuit breakers are opened electricaly by relay or automatic triping device action on circuit breakers. So, it affects the load that is supplied by buses that is why false tripping is not acceptable. Due to these faults and drawbacks, the equipment design should be fault proof. By using high speed protective relaying, one can minimize the damages and adverse effects on the power system (Bhalja and Chothani, 2011).

Our system is based on differential bus protection (Andrichak and Cardenas, 1995) (Kennedy and Hayward, 1938). It is one of the most sensitive and reliable method for protection. The configuration of the busbar protection involves Kirchoff's current rules (which states that the sum of currents entering a node is zero) therefore, the total current entering into a bus is equal to the total current leaving the bus section.

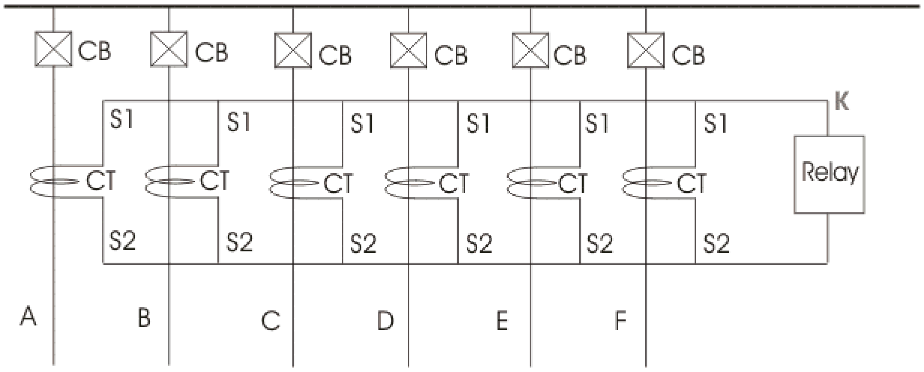


Figure 2.2 General configuration of relays

Figure 2.2 displays the principle of differential bus bar protection which is quite simple. It shows that if any fault occurs, the circuit breaker will open and power flows into other branches.

2.3.1 Sizing of Cables

Proper sizing of cables is essential in electrical circuits, so that the system can operate properly under full load without being damaged. Selecting cables with small cross sectional area can cause voltage drop and poor performance. Meanwhile, selecting too large cables increases cost and weight. Short circuit causes extreme stresses in the cable which are directly proportional to the square of the current, which causes temperature rise in the conductor and later in the insulation material. Short circuit current also produces electromagnetic forces between the current carrying components. Temperature rise has effects on the aging of cable; sometimes it can increase enough to meltdown insulation therefore it is important to ensure that the cable can provide suitable voltage to the load and the cable can withstand the worst case short circuit current. While choosing the appropriate cable, there are some features which have to be considered:

1. Basic Cable Data

   Basic data includes fundamental characteristics of the cable such as

   - Conductor material e.g copper or aluminium.
   - Insulation type e.g PVC, XLPE, EPR (for IEC cables, as we are using IEC standards)
   - Number of cores - single core or N cores.

2. Specification of the Load

   Characteristics of the load for which the cable will be used:

   - Source voltage
   - Number of phases e.g single or three phase
   - Full load power factor
   - Full load current
   - Length of cable run from source to load, this length should be more than needed in length.

3. Cable installation

   Characteristics how the cable will be installed:

   - Installation method e.g cable tray, in conduit, against a wall, in air, directly buried etc.
   - Cable spacing
   - Soil thermal resistivity (for undergroung wiring)
   - Cable grouping, i.e number of different or same type of cables in the same area
   - Ambient temperature of the site

4. Cable selection based on Ampacity

   Ampacity is the current carrying capacity of the cable without exceeding its temperature rating. As current flows through the cable, resistive losses cause heating. So, the cable should withstand that temperature rise without damaging insulation. A cable with larger cross sectional area has a higher ampacity and lower resistive losses. The resistance is expressed as:

$$R = \rho \frac{L}{A} \tag{2.8}$$

where L is the length of the cable, A is the cross sectional area, and ρ is the resistivity constant of the cable.

There are international standards which cable manufacturers usually quote for base ampacities (Anders, 1997).

If the ambient conditions are different from those mentioned in the standards then, there are procedure defined to be followed.

5. Cable selection based on voltage drop

   Whenever current flows through a conductor, there is a voltage drop in it. Voltage drop depends on the current flow and the cable impedance according to Ohm's law.

   The impedance is a function of the cable size (cross sectional area and length of cable) and it's unit is ohms/km or ohms/ft.

   The load power factor is commonly used to find out the voltage drop in AC systems.

   For a 3-phase system, the voltage drop is

   $$V_3\phi = \frac{\sqrt{3}I(R_c cos\phi + X_c sin\phi)L}{1000} \tag{2.9}$$

   For a single-phase system, the voltage drop is

   $$V_1\phi = \frac{2I(R_c cos\phi + X_c sin\phi)L}{1000} \tag{2.10}$$

   where V is the single or three-phase voltage drop (V), I is the nominal full load or starting current (if there is any motor involved) (A), R_c and X_c are the AC resistance and the AC reactance values of the cable respectively (Ohms/km or Ohms/ft), $cos\phi$ is the load power factor (pu), and L is the length of the cable (m or ft).

   When sizing for cables is based on the voltage drop, the smallest cable size that meets the voltage drop limitation is selected. For example, suppose that a 7% maximum voltage drop is specified. 5 mm2, 10 mm2 and 25 mm2 cables have voltage drops of 6.4%, 8% and 4.2% respectively. Then the 5 mm2 cable is selected as it fulfilles the criteria (max. 7% drop).

6. Cable selection based on Short Circuit temperature increase

   While in short circuit conditions maximum current flows, the increased temperature affects the conducting material and the insulation. So, for minimum cable size which can stand the short circuit current the following formula is used:

$$A = \frac{\sqrt{I^2}}{k} \tag{2.11}$$

   where A is the cross sectional area of the cable (mm^2)
   I is short circuit current
   k is the short circuit temperature constant.

   The temperature rise constant k is found by (Commission et al., 2010):

$$k = 226\sqrt{\ln\left(1 + \frac{\theta_f - \theta_i}{234.5 + \theta_i}\right)} \tag{2.12}$$

   where θ_i and θ_f are the intial and final temperature respectively.
   The following temperatures shown in Table 2.1 are commonly used for different insulation materials:

Table 2.1 Operating Temperature of Cable

Material	Max Operating Temperature ^oC	Limiting Temperature^oC
PVC	75	160
EPR	90	250
XLPE	90	250

For maximum available fault current calculation, a temperature of 20^oC is considered. For minimum available fault current calculation, the following temperature values are used: 160^oC for polyvinyl chloride (PVC) insulated cables with cross sectional area $< 300mm2$, 140^oC for PVC insulated cables with area $\geq 300mm2$, and 250^oC for cross-linked polyethylene(XLPE) and ethylene propylene rubber (EPR) cables (Thue, 2016)(Lemke, 2013).

Moreover, the cross sectional size of the cable can be found out by the following formula (Nataraj et al., 2017):

$$A = \frac{I\sqrt{t}}{K} \tag{2.13}$$

where I is the r.m.s value of SSC, t is triping time of the circuit breaker (short circuit breaker), and K is the short circuit temperature constant. Practically, the value of 't' is taken as 0.25 seconds for circuit breaker controlled motor feeder, 0.02 seconds for fuse contactor motor feeder, 0.5 seconds for cables on the primary side of the transformer, and 1 second for cables on the secondary side of transformers.

2.4 The Simulation Environment

In the simulation environment, we have the following components:

1. Bus bars

   Bus bar is actually a metallic bar mostly made up of highly conductive material, as used in switchgears, panel boards etc. It has many advantages in load flow systems. Buses are divided into three categories which are PV bus, PQ bus, and slack bus (Grainger et al., 1994). The slack bus is also called infinite bus as its capacity is larger than the other buses. It is used as the reference bus by which phase voltages are calculated for other buses. Practically, the slack bus is kept out of the iterative solution process; its specification is calculated by using iteration results. Nowadays, because of the existence of distributed generators, the slack bus is not used as a infinite bus due to their comparably small sizes. The high current capacity is essential for current bus types so that they are suitable for electrical installations. (Kabir et al., 2014)

2. Transformers

   A transformer is a static electromagnetic device which consists of windings with or without magnetic cores forming mutual pairs between electric circuits. Transformers are used to transfer power at the same frequency but different in voltages and currents. Transformers form the main components of distribution and transmission systems of electrical energy. Their design is based on their application area. There are many types of transformers according to their use (Harlow, 2012).

   A power transformer is defined as a transformer that transfers electrical energy from the generator to primary distribution networks. Transformers that are directly connected to the generation side are called generator transformers. Their capacity is generally 1000 MVA and 1500 KV for power and voltage respectively. Also, different types of transformers are produced such as network transformers, autotransformers, and distribution transformers. Distribution transformers are used in systems where electrical energy is transferred from a medium voltage system to a low voltage system. Transformer design is a complex task for engineers as compatibility with the synchronization specification has to be ensured. The high cost is also a factor for manufacturers. The design procedure may vary greatly depending on the adapter type (distributor or converter), operating frequency (50/60 Hz), cooling method, and type of magnetic content (Amoiralis et al., 2009). There is one terminology taping of transformer by which you can select the different turn ratio and be able to control the voltage regulation. If we need the higher voltage on output end we can increase the taping of secondary winding by which the secondary voltage will be increased and in most of the industrial area auto tapiing is used.

3. Switchgears

   Switchgear is a typical term describing metal-clad switches or circuit breakers. Switchgear is an electrical equipment that regulates the electricity within an electrical system. It is used by utility providers and private facilities for two reasons: to prevent overloads and short circuits; and to de-energize circuits for testing and maintenance. The most familiar types of switchgears are circuit breakers and fuses, which interrupt the flow of electricity to a circuit when its current becomes too high. Then there is a need to switch from a basic source to a secondary generator. There are five types of switchgears available today in the market based on the type of material used for separation: air, oil, gas (SF6), vacuum and hybrid.

4. Generators

   Generator is a machine which generates electricity with the use of external energy sources e.g. wind, gas etc. by converting mechanical energy into electrical energy. Generators are basically divided into two types: AC and DC generators. Synchronization is a term used in generators or motors when the rotor and the magnetic field rotate at the same speed. A synchronous generator is a device that converts mechanical energy as output of a hydro turbine, steam turbine etc. into electrical energy in such a way that the frequency of the induced voltage on the stator winding is proportional to rotor revolution per minute (RPM). The synchronous generator is also called as an alternator. Synchronous generator is the main component in a power generation house for electricity especially for high power generation. In synchronous generators, the energy conversion is done on the basic principle of electromagnetic induction. According to Faraday's law of electromagnetic induction, EMF will be induced in winding if the coil rotates in a static magnetic field or if the magnetic field rotates with respect to the static coil. In a synchronous generator, the magnetic field is made to rotate with respect to the static coil to generate voltage in the stator windings. Synchronous generators are considered for use in our analysis. Since the synchronous generator is the main component in the power house and very big in size, we cannot have a generator with a small number of poles for that purpose. If the number of poles is small, then in order to achieve the required frequency, the rotor has to move at a very high speed that can be very dangerous. Moreover, high speed will result in a large magnitude of centrifugal force that can break the bearing and eventually the stator winding. For that reason, a high number of poles are used for the generator (Perers et al., 2007). Synchronus generators provide the constant frequency i.e. 50 or

60 Hz throughout the generation. They may be driven by steam turbines, hydropower, gas turbines, internal combustion engines, pneumatic motors, and electric motors (Zhu and Howe, 2007).

5. Lump Load

   Lump load is a type of network including different kinds of loads such as resistive, capacitive, and inductive load. In our simulation environment the lump load consists of motors and resisitive loads so that you can set how much of the load should be resistive and inductive.

   Table 2.2 shows the lump load configuration, which is connected tomain bus bar. These consists of 80% inductive (motor) load and 20% static load where the total rating is 123KVA.

   Motor load and static load are adjustable in the simulation software; further, the rated values of kVAR, kW, power factor etc. are also shown in Table 2.2. Whenever there is a power transmission system, lump loads are involved. In a long transmission system there are three factors which play a vital role in designing of insulators.

   - Resistance
   - Inductance
   - Capacitance

   which can be calculated as the resistance per meter, inductance per meter, and capacitance per meter easily, following table 2.2 shows the different inpur values that is usually taken as input for designing of system.

Table 2.2 Lumped Load input

Lump Load ID	kVA
Lump 1	5.6
Lump 2	6.1
Lump 3	10.1
Lump 4	42.6
Lump 5	20.3
Lump 6	38
Lump 7	27
Lump 8	15.3
Lump 9	20.6
Lump 10	5.8
Lump 11	5.8
Lump 12	3
Lump 13	14
Lump 14	18.8

6. Motor

   There are many kinds of motors used to convert electrical power into mechanical power. In our modeling, induction motors are employed for the analysis. Induction motor is an AC motor in which the torque in the rotor is produced by electromagnetic induction. It is a self starting motor without need of a variable frequency drive (VFD) for starting. Three phase induction motors will be considered which are the most commonly used motors in many applications. These are also called as asynchronous motors because an induction motor always runs at a speed lower than the synchronous speed (speed of the rotating magnetic field in the stator). There are basically two types of induction motors depending upon the type of input supply:

   - Single phase induction motor
   - Three phase induction motor.
   - Squirrel cage motor

- Slip ring motor or wound type

  In a DC motor, the stator and the rotor both need their separate electrical input to start. But in an induction motor, only the stator winding needs an AC supply, by which changing flux produces the induction current. This alternating flux runs in a synchronous speed. This alternating flux is called as "Rotating Magnetic Field" (RMF). The relative speed between the stator RMF and the rotor conductors produces an induced emf in the rotor conductors, according to the Faraday's law of electromagnetic induction. The rotor conductors are short circuited, hence a rotor current is produced due to the induced emf. That is why its also called as induction motors. This action is similar to the operation of transformers, hence induction motors can be called as rotating transformers. The induced current in the rotor will also produce alternating flux around it. This rotor flux lags behind the stator flux. The direction of induced rotor current, according to Lenz's law, is such that it will tend to oppose the cause of its production. As the cause of production of rotor current, the relative velocity between rotating stator flux and the rotor, the rotor will try to catch up with the stator RMF. Thus the rotor rotates in the same direction as that of stator flux to minimize the relative velocity. However, the rotor never succeeds in catching up the synchronous speed. This is the basic working principle of an induction motor of either type, single phase or 3 phase.

  The rotational speed of the rotating magnetic field is called as the synchronous speed, given below.

  $$Ns = \frac{120f}{P} \tag{2.14}$$

  where,

  N_s is the synchronous speed, f is the frequency of the supply, and P is the number of poles.

The rotor tries hard to match with the speed of the field, thus it rotates. But practically, the rotor cannot match the speed of the stator. If the rotors frequency is equal to the stator frequency then, there will be no relative speed between the rotor and stator. The emotor can heat up and the winding can be damaged or there will be an explosion. Furthermore, there would be no induced current and no torque will be produced. However, it will not stop the engine, it will slow down due to the loss of the rotor, the tackle will return due to the high speed. So the rotor speed is always less than the synchronous speed. The difference between the compatible speed (Ns) and the actual speed (N) of the rotor is called the slip, and the percentage slip is expressed as below.

$$s = \frac{N_s - N}{Ns} \tag{2.15}$$

This motor is widely used in industrial applications because of the low maintenance costs as there are no brushes. Induction motors can be used in electric trains, cooling fans used to cool large machines like alternators, chimneys at power plants, printing machines, and rolling mills.

3. METHODOLOGY

3.1 Inputs Required For Load Flow Analysis

In this section, the required inputs for modeling an electrical system in the simulator software for load flow analysis and short circuit analysis, are discussed . If input data are not available, standard values can be used to follow the procedure. A simulation environment needs a lot of information for modeling.

1. Power grid input

   Power grid is taken as a primary source and there are many modes available (swing, V control, MVAR etc.) for the power grid. Generally, the swing mode is used for power grids. In this mode V and σ are used as an input. Impedance can also be modelled for the grid but mostly the simualtion engine uses V, σ , P, Q, Qmax & Qmin values for this analysis.

   In this work, a 13.8 KV power grid in swing mode is used, as shown below in Table 3.1 where the parameters required for designing the power grid are displayed.

   Table 3.1 Power Grid Input

Rated KV	SC Rating	X/R
13.8	1250	20

2. Generator input

   For generators, typical inputs will be used such as rated power (MW), rated voltage (V), rated efficiency, and rated power factor (Commission et al., 2010). Table 3.2 displays the inputs that are used to model a generator.

Table 3.2 Rating Value of generator

Rated KW	KVA	%PF	% eff	Poles	RPM	FLA
213	250	85	95	4	1500	24.06

3. Transformer input

   The primary voltage, secondary voltage, X/R ratio, impedance, rated apparent power, tap positions, and impedance tolerance value are used as inputs for a transformer (Commission et al., 2006)
   (Harlow, 2012). If copper losses are not available then typical values will be used (Georgilakis and Tsili, 2007). If the transformer is of type On Load Tap Changer (OLTC) and Automatic Voltage Regulator (AVR) then lower & upper bands of voltage in %, minimum and maximum tap and step size are also needed as an input. Tap position is variable in adjusting the upper band and lower band of bus voltages as it increases the turn ratio of the secondary side (Fletcher and Stadlin, 1983).
   In our simulations, two step down transformers with different rated values are used as follows:

Table 3.3 Rated value of T1

Prim KV	Seco KV	Typical X/R	FLA
13.8	11	5.79	31.38

Table 3.3 shows a stepdown transformer with 13.8 KV at the primary side, and 11kV at the secondary. The primary of this transformer is connected to the power grid and the secondary is connected to the primary side of the second transformer. Typical values are used for impedance because of the unavailability of copper losses.

Table 3.4 Rated value of T2

Prim KV	Seco KV	Typical X/R	FLA
11	4.4	5.79	26.24

Table 3.4 shows a step down transformer (11kV to 4.4 KV) where the secondary side is conncected to the load via bus bars.

4. Lump load input

   Low voltage loads are modeled as lump load. It consists of the actual active and reactive power connected to the bus. The bus provides input to the lump load. Percentage of the static load and motor load can be set. The total load of the system is 227.2 kVA which is divided into 14 branches as shown below in Figure 3.1.

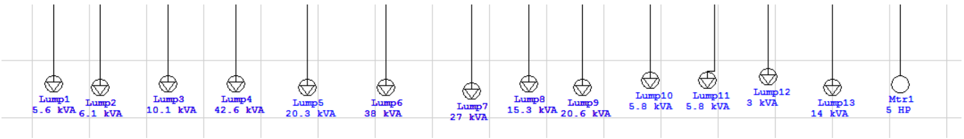


Figure 3.1 Load branches

3.2 Inputs Required In Short Circuit Analysis

For the maximum and minimum fault currents to be calculated two different scenarios are needed where the following inputs are required.

1. Power grid input

   The rated voltage and impedance values, three phase or single phase apparent power, and the X/R ratio are used for the short circuit analysis (Commission et al., 2001). Usually, the maximum and minimum apparent power values are provided by the manufacturer which are used to find out the maximum and minimum fault currents respectively (Prajapat et al., 2016).

   Further inputs used in short circuit calculations are same as in the load flow analysis (Table 3.1).

2. Generator input

   The rated voltage, power, power factor, d-axis sub transient reactance (Xd), d-axis transient reactance(Xd), d-axis and q-axis reactances (Xd and Xq), negative sequence reactance (X2), Zero sequence reactance (X0), armature resistance (Ra), negative sequence resistance (R2) and zero sequence resistance (R0) are required for modeling of a generator. This information is usually provided by the manufacturer. If the above data are not available, typical values can be used.

3. Transformer input

   The rated voltage, apparent power, and zero sequence impedance with X/R ratio are the common inputs used for analysis. The impedance of the transformer can be chosen by (Commission et al., 2006). Higher values of impedance are used when the current in the secondary side of the transformer should be reduced. The X/R ratio is calculated using copper loss and impedance of the transformer.

4. Busbar input

   The nominal voltage of the busbar is an important input for short circuit calculations. In IEC based projects, the busbar voltage is different from the secondary side of the transformer, so the nominal voltage is based on the secondary voltage of the transformer.

3.2.1 Configuration of Load Flow and Short Circuit Analysis

This section explains the details of the electrical system implementation. As this system is aimed to be used in warehouses, oil & gas plant etc., there are N+1 generators and transformers for backup in this design. In simple words, if one of the transformers, generators or power grid is out of service then the remaining N generators operate and they can supply power to entire load (Prabhu et al., 2016). Multiple study case scenarios are formed to analyze the load flow or power flow in the following types of operation:

- Maximum load
- Normal load
- No load
- 25% of load
- 50 % of load
- 75 % of load

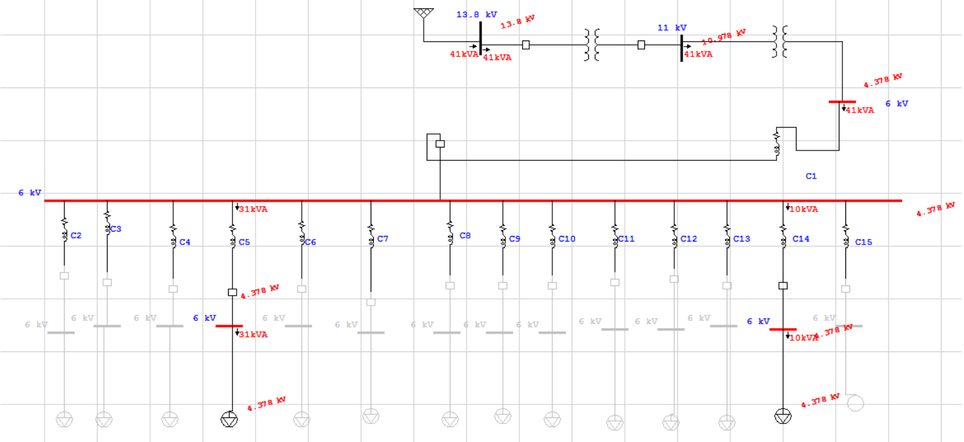


Figure 3.2 Load flow analysis with 25% of load

Figure 3.2 shows the case for 25 percent of total load which is 56.8 kVA. In this case we are checking the behaviour of the system in order to identify which factors will increase or decrease the perfromance metrics. We also display the 50% and 75% of load cases in Figure 3.3 and Figure 3.4 respectively. Further details about the system behaviour will be described in the next section.

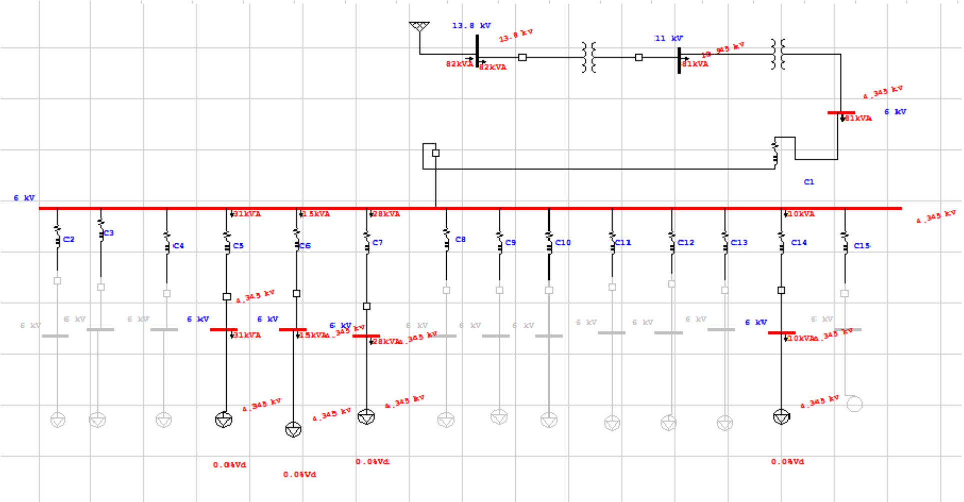


Figure 3.3 Load flow analysis with 50% of load

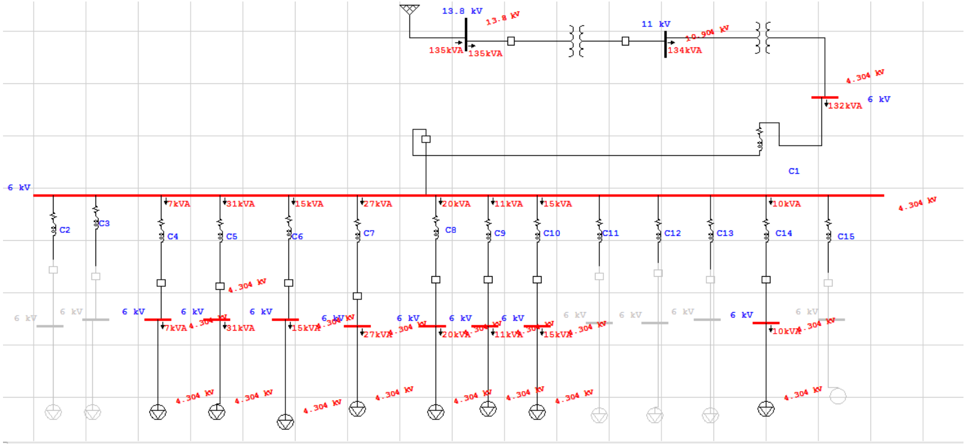


Figure 3.4 Load flow analysis with 75% of load

Power flow analysis under normal case is performed to find the voltage, power factor, and the losses. In this case, every source (generator and grid) will work together as shown in Figure 3.5.

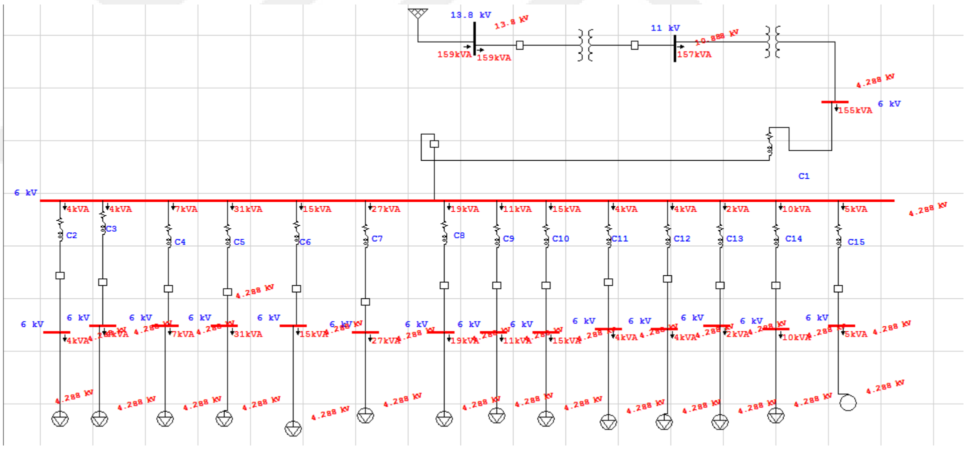


Figure 3.5 Load flow analysis with full load by using power grid

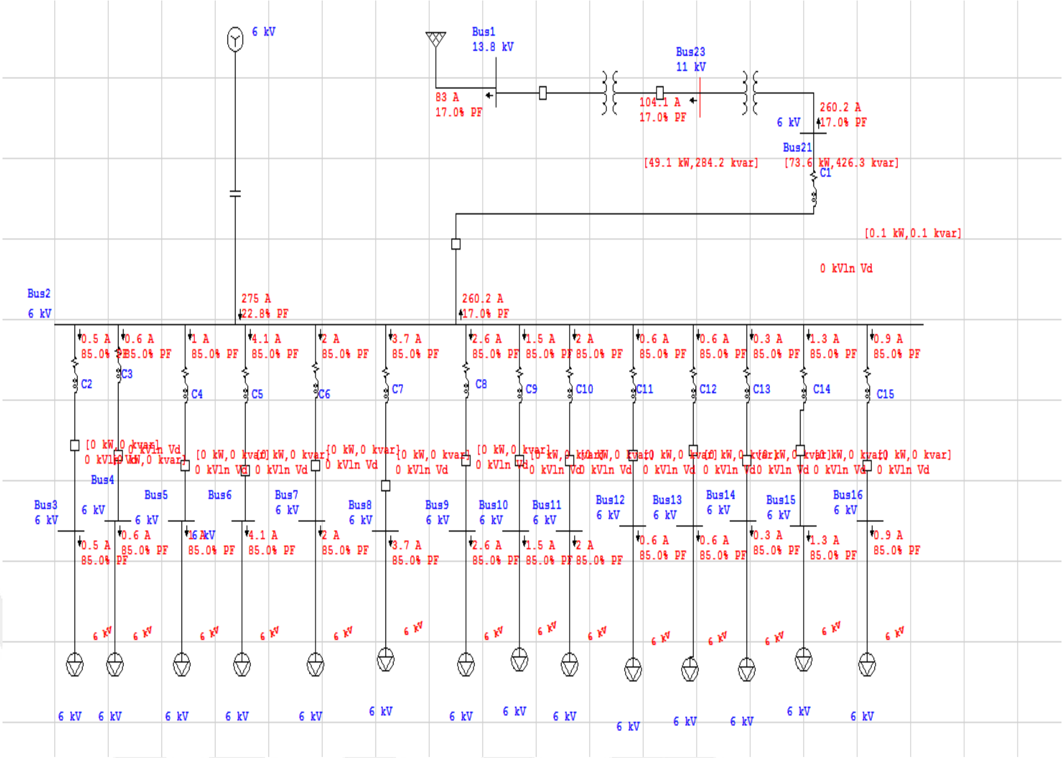


Figure 3.6 Normal load flow operation

In the normal load case as shown in Figure 4.5, maximum load on the sources are used which includes the power grid and generators, in which we can see the capability of our system to withstand it or not. Voltages on switchgears (circuit breakers) will be minimum hence worst case minumum voltage of circuit breakers is calculated in maximum load operation as shown in Figure 3.9.

In the no load case we can find the voltages on the switchgears. As it is a no load case, no current will flow in the transformer. If the transformer is at no load, then its secondary winding is an open circuit, in other words, no load is connected to transformer. When an AC source is connected to the primary winding of a transformer, a small current, $I_(open)$ will flow through the winding of the primary coil due to the presence of the primary supply voltage. With the secondary circuit open, nothing connected, a subsequent EMF, together with the primary resistance of the winding will be produced which will act to limit the flow of this primary current. Obviously, this primary current with no load (Io) must be large enough to maintain a sufficient magnetic field to produce the corresponding emf (Figure 3.7).

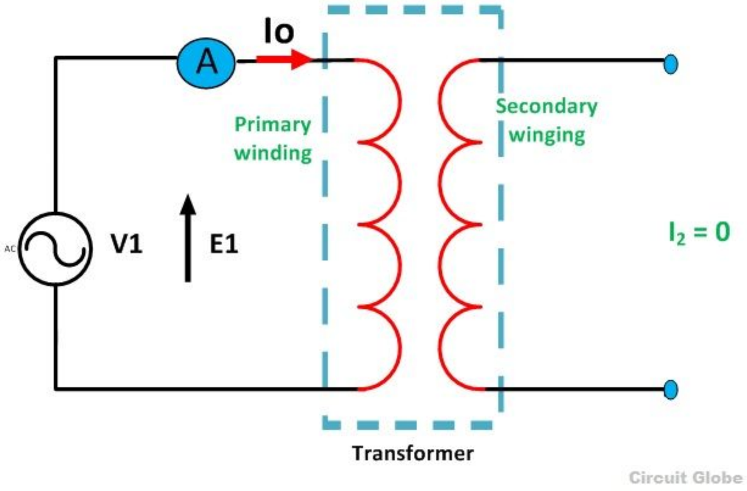
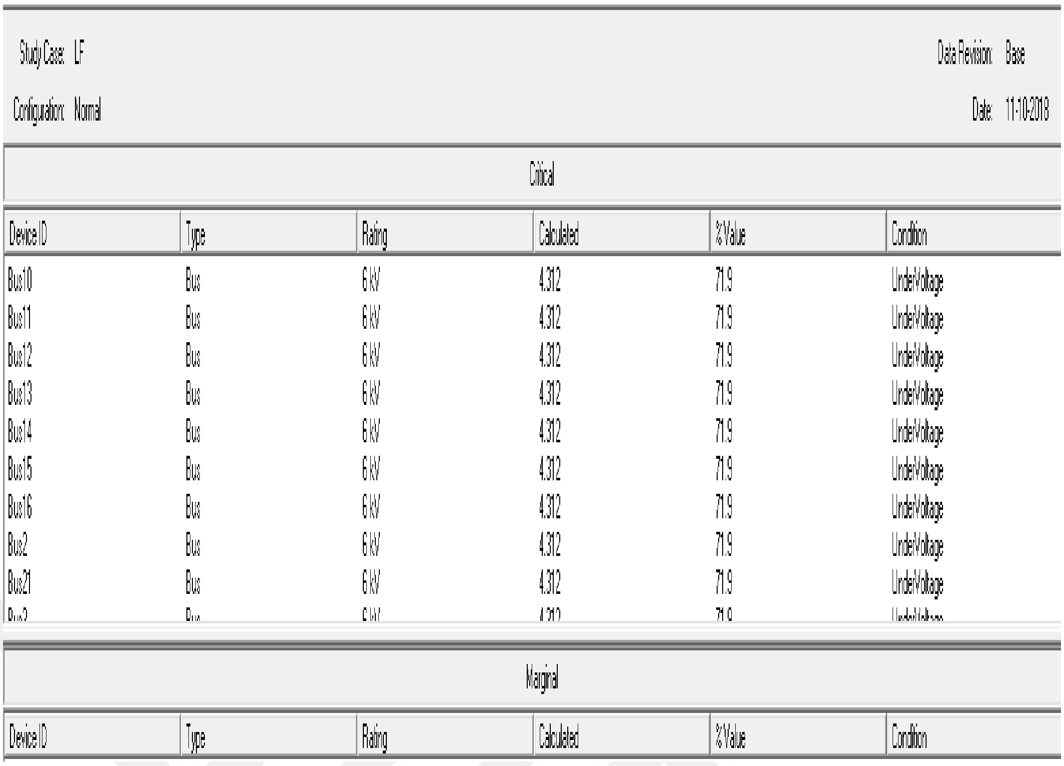


Figure 3.7 Transformer at no-Load

For loadings of 25%, 50% and 75% of the total load (181.76KW), analyses are carried out to check the behaviour of the system. One of the major problems faced in power systems is the occurrence of under voltages and over voltages which can be caused by many factors. As the reactive power cannot be transferred to long distances, especially under the full load conditions, the generation has to be performed near the consumers which is not much practical because of many reasons. So, if it is not available near the load location, the voltage goes down and because of this under voltage damage can be caused in the load, specially in motors. This damage is triggered by the heat up and it can burn and explode windings (Baby and Sreekumar, 2017)(Mozina, 2007). In this case, under voltages occur on every bus, as it happens when voltage drop is 90% of the rated value and the line demands more power then they are delivering, as this problem will be solved later. There is an option in the simulation environment that you can find out whether your system will face severe damages or not (Kapahi, 2013). Figure 3.8 displays the under voltage on different bus bars.



Study Case: LF

Configuration: Normal

Data Revision: Base

Date: 11-10-2018

Critical

Device ID	Type	Rating	Calculated	%Value	Condition
Bus10	Bus	6 kV	4.312	71.9	UnderVoltage
Bus11	Bus	6 kV	4.312	71.9	UnderVoltage
Bus12	Bus	6 kV	4.312	71.9	UnderVoltage
Bus13	Bus	6 kV	4.312	71.9	UnderVoltage
Bus14	Bus	6 kV	4.312	71.9	UnderVoltage
Bus15	Bus	6 kV	4.312	71.9	UnderVoltage
Bus16	Bus	6 kV	4.312	71.9	UnderVoltage
Bus2	Bus	6 kV	4.312	71.9	UnderVoltage
Bus21	Bus	6 kV	4.312	71.9	UnderVoltage

Marginal

Device ID	Type	Rating	Calculated	%Value	Condition

Figure 3.8 Under voltages alert

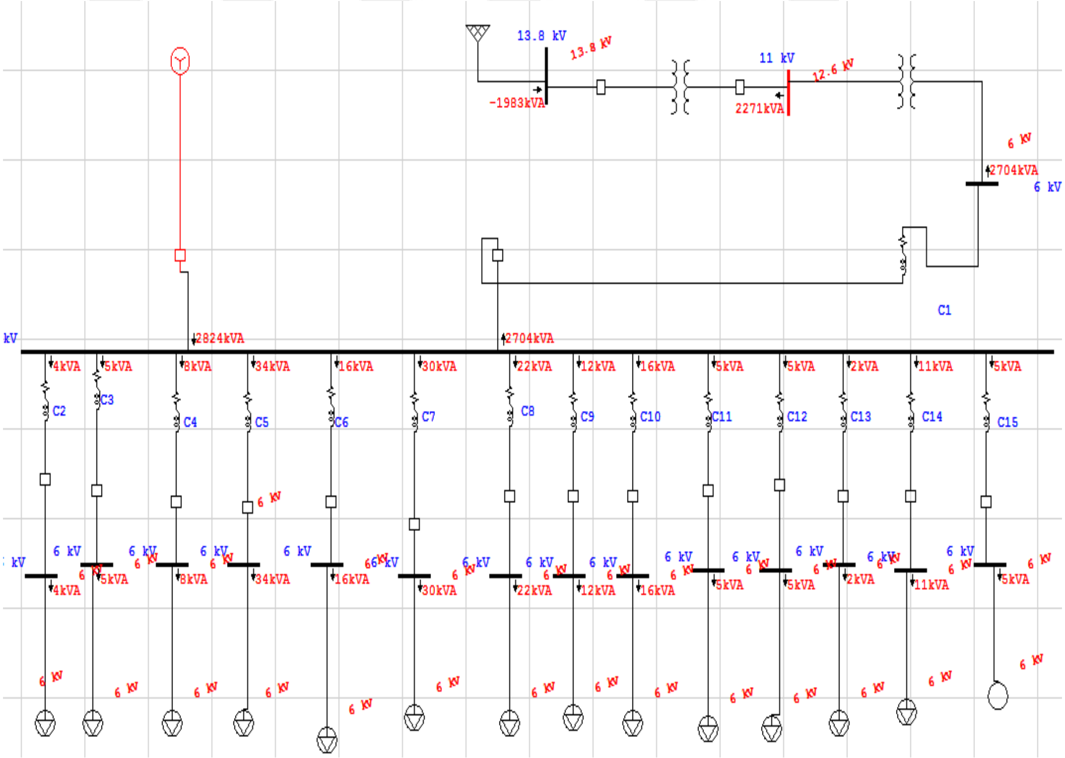


Figure 3.9 Solution of under voltages (maximum load operation)

As a single transformer cannot handle the total load demand, it can be suggested to use two sources together. So, a generator is employed along with the power grid which is also very important in case of unavailability of the power source. If one line is unavailable that is if the power grid is out of service we can still fulfill the load demand. This can be achieved in multiple ways by using different orientation of switchgears, using circuit breakers, switches, and fuses.

Some of the commonly used switchgear configurations implemented in power systems are as follows:

- Double ended switchgear
- Switchgear connected by generator and power grid
- Switchgear with parallel operation between generator and power grid

As we are using a single bus bar to connect N+1 generators and power grid, two different circuit breakers have to be used before the bus bar which are connected to the sources.

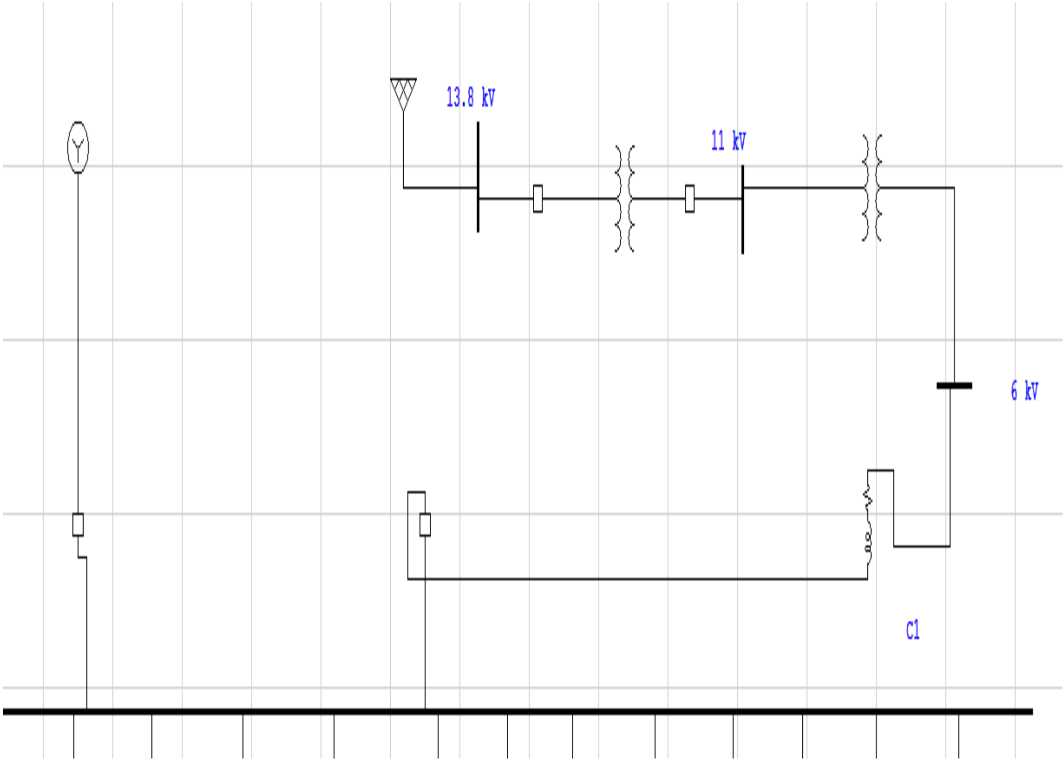


Figure 3.10 Switchgear configurations

Figure 3.10 shows the switchgear configuration which is also beneficial for the protection as both lines have separate circuit breakers with different ratings. If a problem occurs in one of the lines, the load will still run. However, the generator's voltage doesn't match with the power grid voltages for most of the times, so transformers have to be inserted between them. In some scenarios, the generators are used to supply the total load and also give some power to the grid. If the generator gets out of service then the whole system gets down.

Sometimes the generators are designed to give a certain fraction of the supply to the system and the rest is supplied by the grid which is the case considered in this work. If the generator gets out of service then the entire load will be run by the power grid so that the transformer should be sized enough for supplying the total load for the plant which is a kind of normal operation. For maximum load conditions the generator has to be taken out of service as can be seen in the configuration of Figure 3.5.

For the no load operations, one source can be utilized. Mostly the power grid is used in that case where the voltages on bus bars have to be determined. As we are using bus differential protection discussed in section 2.5, if any fault occurs in any one of our feeders that circuit breaker will be tripped and there will be no effect on other loads, but the load connected to the faulty branch should be transferred to other branches.

Meanwhile, short circuit analysis is usually done for maximum available fault current and minimum fault current in the system. Maximum available fault current is used for checking the withstand capacity of the electrical eqipment. We can find the maximum fault current by designing the proper earthing system where current flows from line to ground (LG). Minimum fault current is used to select the overcurrent relays, so that short circuit calculation time is reduced. The configuration status can be used to develop different scenarios or modes in the design of the electrical system. ON/OFF operation can be controlled by devices like circuit breakers, switches, etc.

For example, if we want to use the system in the ON configuration then the same switching device can be utilized for the OFF mode.

For maximum available fault current analysis ON/OFF switch mode shall be developed to get the maximum fault current and this is not the same for every model. Conditions mentioned below shall be used for closing and opening switching devices.

- Power grid model with maximum short circuit current will be chosen.
- Parallel operation for transformer, generator, and grid can be considered together. Usually this scheme is used when the system voltage is 33kV and above and when there is the need for a standby generator in case of emergency supply.
- Motors will be considered as loads (except spare ones).
- Practically, in oil and gas projects, the switchgear for systems having a voltage of 11 KV is designed with a single bus bar. Each bus bar is connected with the source via a transformer and the other end is connected to the load. One transformer is capable to provide power to all loads, for this type of arrangement one transfomer can be considered to be in service and the other transformer is kept out of service to be used in case of emergency.
- When current limiters are not available, they will be modeled as a circuit breaker for short circuit analysis. I_s limiter opens whenever a fault occurs and it doesn't operate up or down stream. It will be considered as open for faults at 11kV.

Similarly, for minimum available fault current, the ON/OFF switching device will be modeled as follows:

- Power grid model with maximum short circuit current will be chosen.
- Motor loads will be taken out of service.
- I_s limiter operates as open circuit.

  During the analysis, the results of the following faults will be collected. The initial symmetrical RMS current (Ik), steady state RMS current (Ik), peak current (Ip), and the angle between current and voltage are calculated for the 3-phase faults:

- line to ground (LG) fault.
- line to line (LL) fault.
- double line to ground (LLG) fault.

Study case scenarios are formed to analyse short circuit calculations for:

- 75% of load
- 50% of load
- 25% of load.

While using these loads, faults will be introduced into the system. To run the short circuit analysis, faults should be introduced in the system as we introduced it on different bus bars. Also an arc flash test is run on the main bus for all the cases; this test is important as it tells us about the incident energy (light or heat) caused by touching of 2 different bus phase voltages. Meanwhile, some additional electrical equipments are added to the system by which the response of the system is monitored in different scenarios. For this extended analysis a stepdown transformer is used with ratings of 13.8 KV to 11 kV.

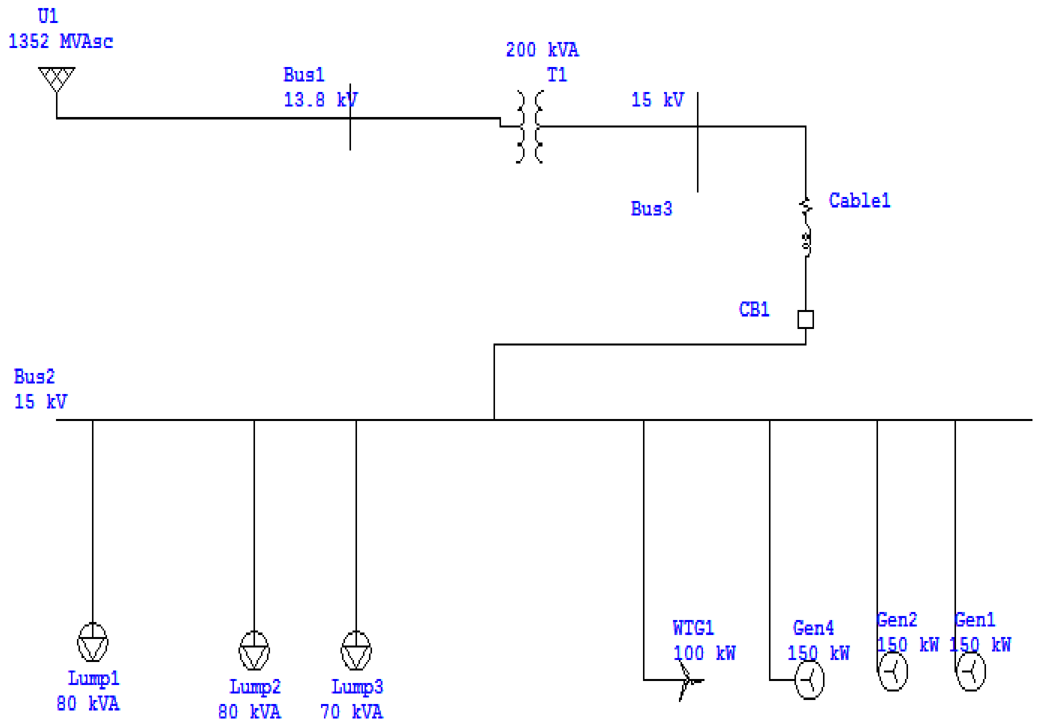


Figure 3.11 Multiple power sources (generator and wind sources) added to the power system

Figure 3.11 shows the power sources added to the system, which can also used be as a separate power source if any of them breaks down we can use as a suplement.

- Three generators (Run with power grid in normal mode operation)

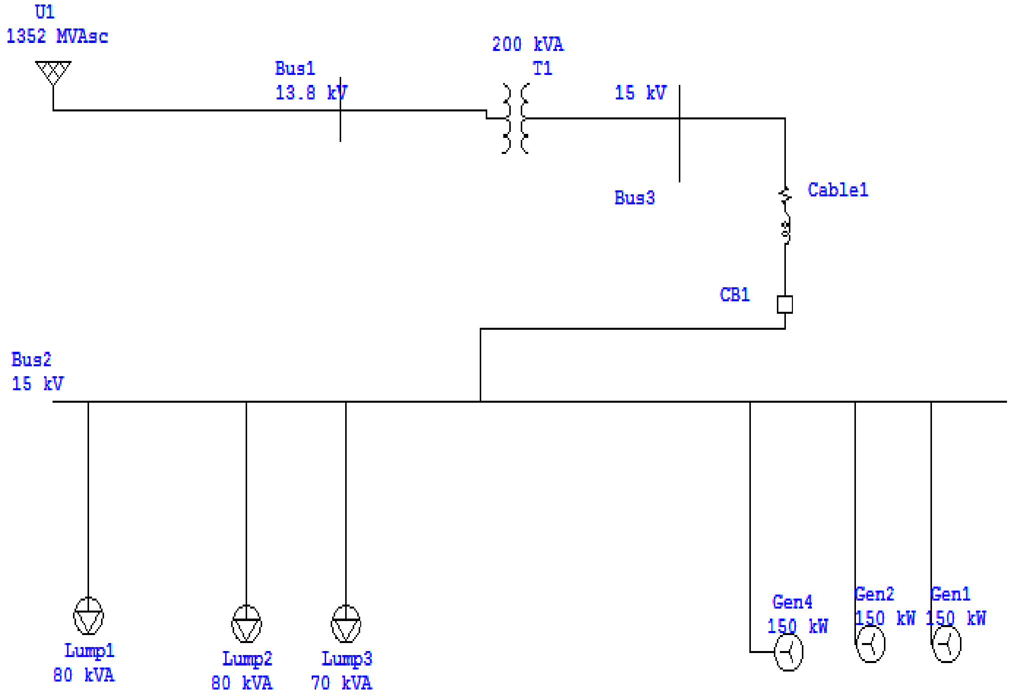


Figure 3.12 Three generator set

Figure 3.12 shows the generator that is working in this system to check the system response.

- Change of cable length (50km, 100km) The length of the connection cable is varied to include two long distance cases, namely 50km and 100km, to check the voltage drop across the bus bars (Figure 3.13).

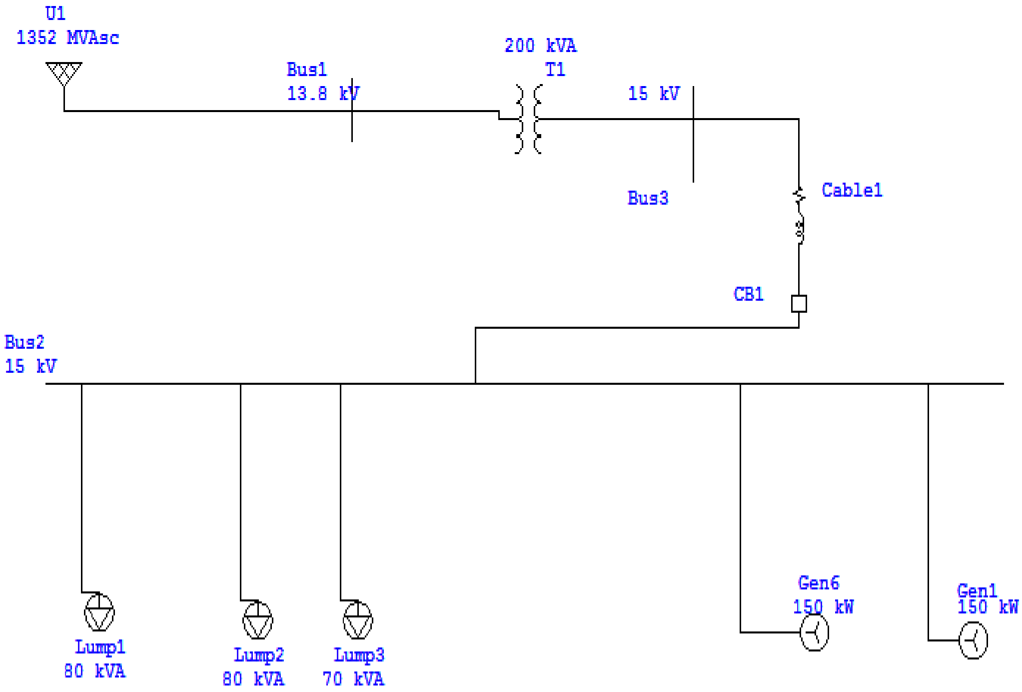


Figure 3.13 Varying of cable length: 50km and 100km

- Wind turbine added in the system (Run with power grid)

  Impacts of changes in cable length and inclusion of extra power sources are disscussed in the results section.

4. RESULTS AND DESIGN RECOMMENDATIONS

In this section, the results based on different scenarios explained above in section 3.1 and in section 3.2, are displayed. Meanwhile, methods will be highlighted on how to design equipments with rated values.

4.1 Load Flow Analysis Results

Load flow analysis has been performed for maximum load, normal load, 25% of load, 50% of load, 75% of load, and no load cases. In the following, the outputs will be shown for different scenarios.

1. Maximum Load Case
   In maximum load operation, the grid will be out of service: the whole load of 232 kVA will be powered by the generator, and using the results, we will analyse the response of the generator. Figure 4.1 shows the maximum load operation with a generator.

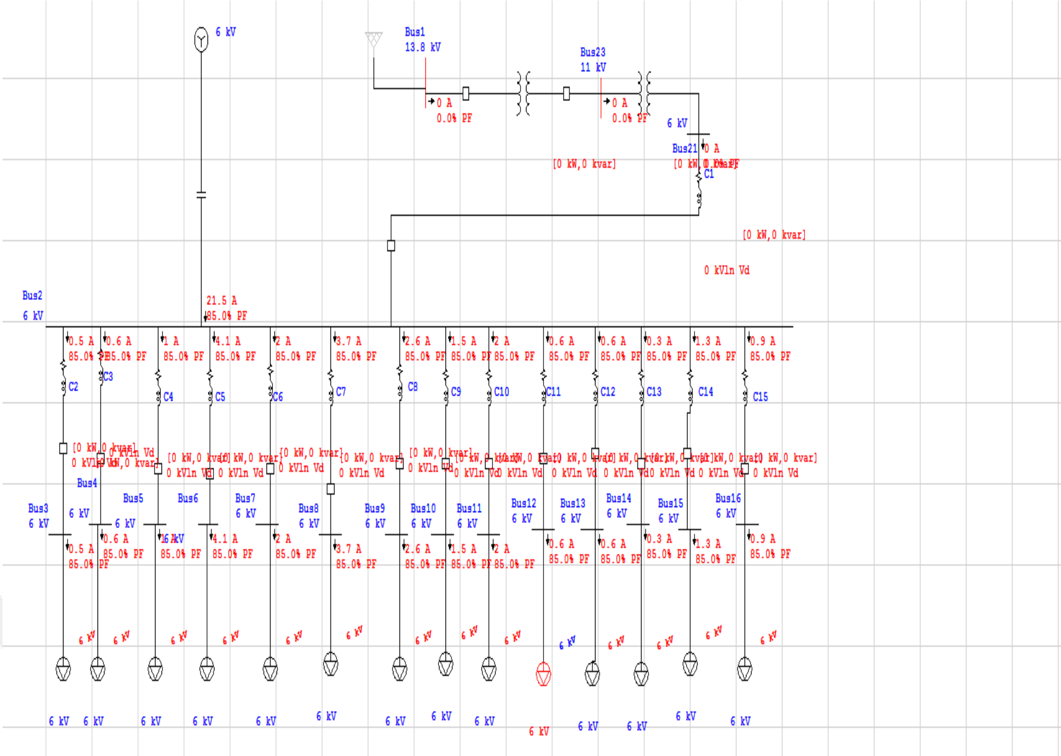


Figure 4.1 Maximum load flow operation

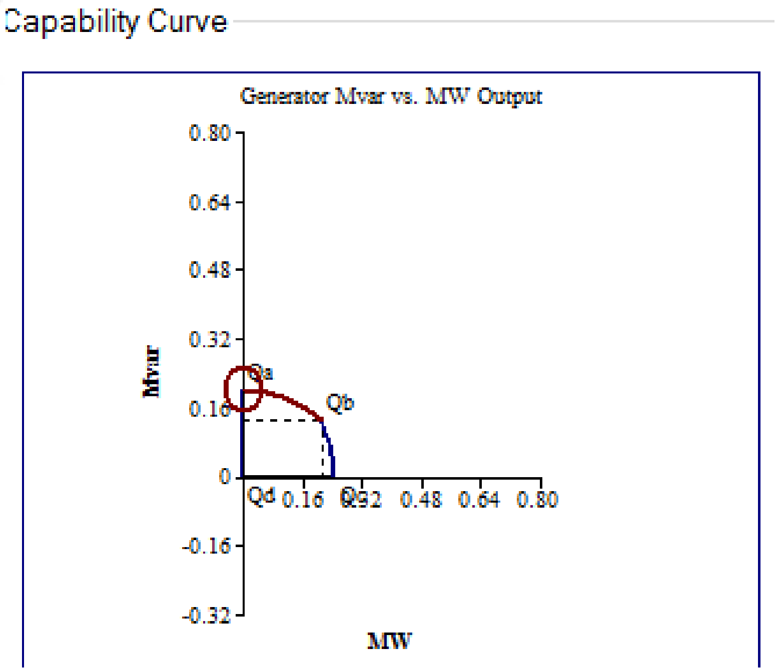


Figure 4.2 Capability curve for the electrical system

The capability curve of the generator shows the boundary of regions in which the machine can operate safely (Bharadwaj and Tongia, 2003). Usually, the manufacturers provide these kind of data to the consumer. This curve contains one or more boundaries for the megawatt (MW) and megavolt-ampere-reactive (MVAR) ratings. These rated values are designed to keep the generator temperature or electrical insulation below the limits which are described in the American national standards (Nilsson and Mercurio, 1994). The capability curve for our case is given in Figure 4.2.

Harmonics are the unwanted frequencies which are superimposed on the nominal operation frequency. They create the distorted waveforms as shown in Figure 4.3 where both the waveform and the spectrum of the harmonics are displayed.

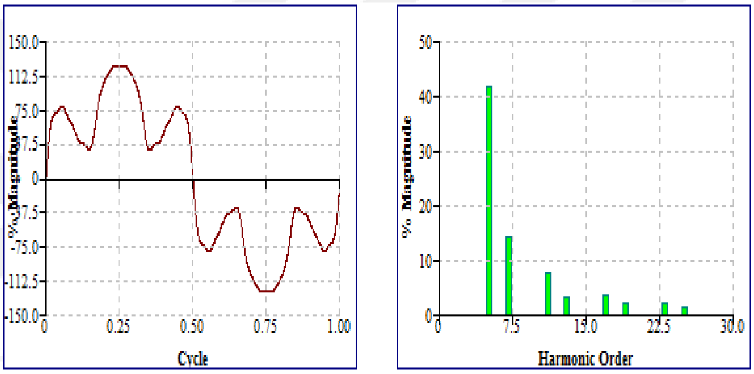


Figure 4.3 Harmonic graph and spectrum

Table 4.1 Summary of Generation, Loading, Demand and Power factor (Maximum Load Case)

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.19	0.118	0.224	85 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.190	0.118	0.224	85 Lagging
Total Motor Load	0.152	0.094	0.179	85 Lagging
Total Static Load	0.038	0.024	0.045	85 Lagging
Total Constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.00	0.00	0.00	

Table 4.1 shows the summary of the generation, loading, demand, and power factor of the eelctrical system. In this case, the motor load is 0.152 MW and the static load is 0.038 MW with 85% PF lagging. Whenever the power factor is between 0 and 1 the system is going alright, in this case, we have 0.85 lagging which is normal. The lagging part shows that there are inductive loads in which currents lag. Normally, the leading power factor is prevented for a system.

Table 4.2 Bus Loading Summary Report

Bus Loading			
Bus ID kV	Generation (MW)	Loading (MVA)	Current (Amp)
Bus 1 13.8kV	-0.000	0.000	0.0
Bus 2 6kV	0.000	0.224	21.5
Bus 3 6kV	0.004	0.006	0.5
Bus 4 6kV	0.004	0.001	0.6
Bus 5 6kV	0.007	0.010	1.0
Bus 6 6kV	0.029	0.043	4.1
Bus 7 6kV	0.014	0.020	2.0
Bus 8 6kV	0.026	0.038	3.7
Bus 9 6kV	0.018	0.027	2.6
Bus 10 6kV	0.010	0.015	1.5
Bus 11 6kV	0.014	0.021	2.0
Bus 12 6kV	0.004	0.006	0.6
Bus 13 6kV	0.004	0.006	0.6
Bus 14 6kV	0.002	0.003	0.3
Bus 15 6kV	0.001	0.014	1.3
Bus 16 6kV	0.006	0.009	0.9
Bus 21 6kV	0.000	0.000	0.0
Bus 23 11kV	-0.000	0.000	0.00

There are 18 buses in total which are working in the system. Bus 1 and bus 23 have rated voltages of 13.8kV and 11kV respectively, the remaining buses have the same rated voltage of 6kV. The currents and power dissipation values are different for every bus due to the fact that those buses are connected to different loads. The detailed list of values is given in Table 4.2

2. Normal case

   In the normal case the generator and the transformer will work together. The generator has the same rated value as in Table 3.2, two step down transformers are used in our system with different rated values as given in Table 3.3 and Table 3.4 for transformer1 and transformer2 respectively. The rated value of the power grid is as shown in Table 3.1.

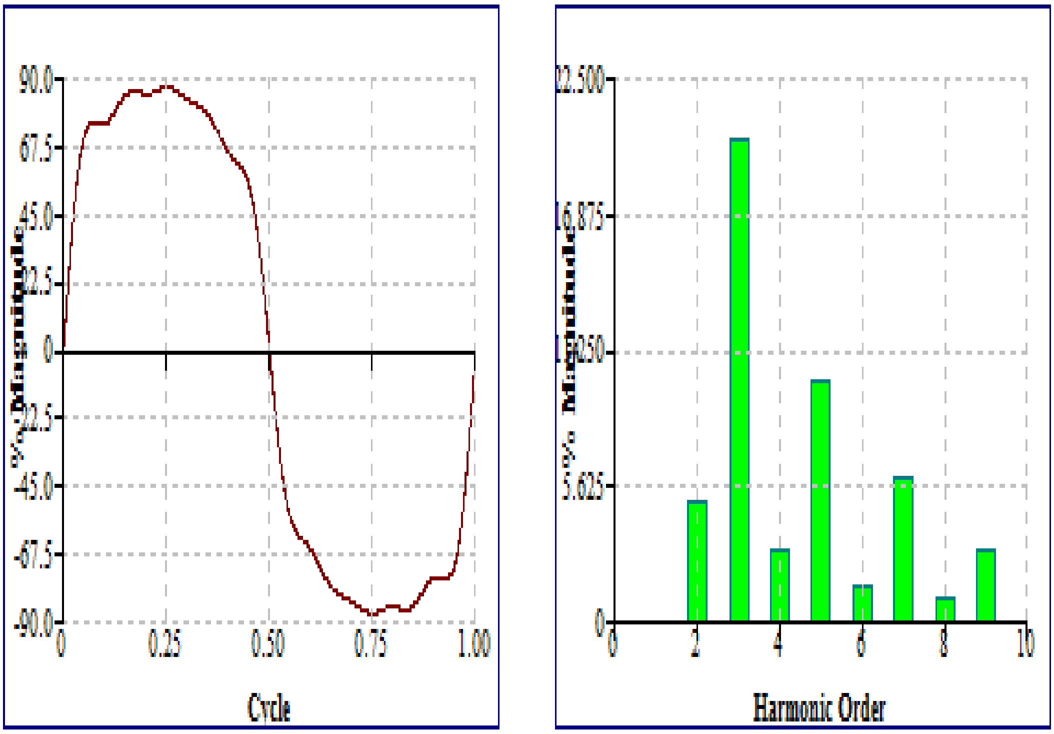


Figure 4.4 Harmonic waveform and spectrum

Figure 4.4 shows the harmonics waveform and spectrum for the grid. Grid harmonics have also destructive impacts on grid components and also on transformers, mostly on distribution transformers. According to a study on current harmonics, there are severe effects on the life of transformers such as eddy current losses, hottest spot temperature, and stray losses (?).

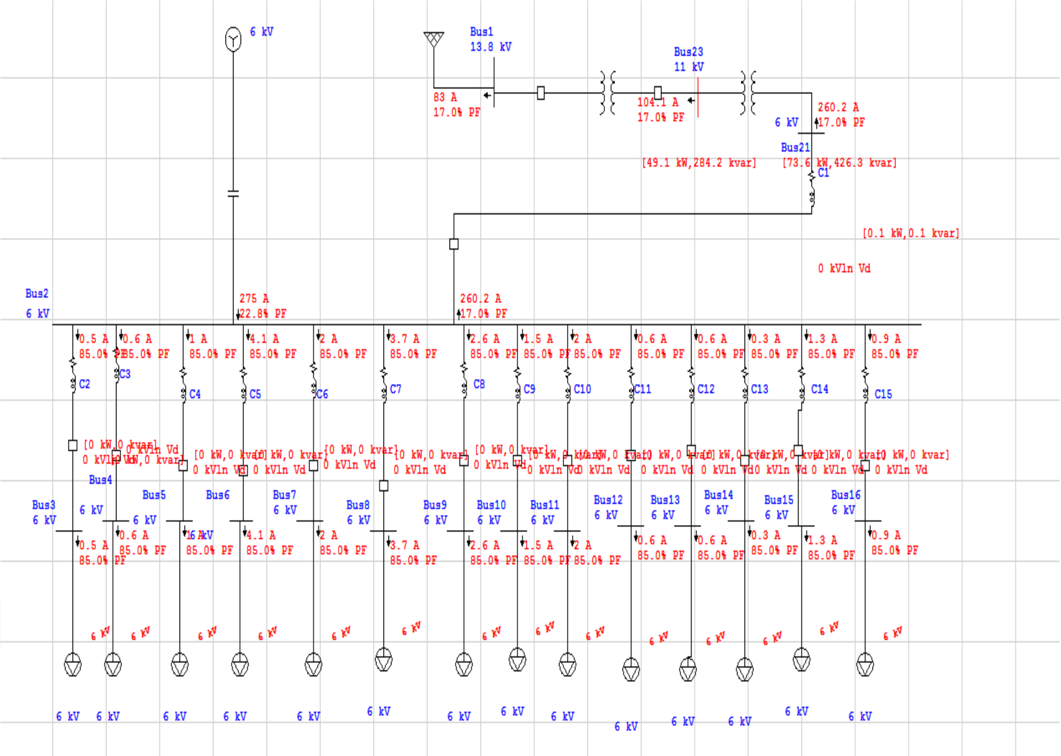


Figure 4.5 Normal Load flow operation

Table 4.3 Output in Normal Load Flow Case

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.173	0.114	0.207	83.47 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.173	0.114	0.207	83.47 Lagging
Total Motor Load	0.152	0.094	0.179	85.00 Lagging
Total Static Load	0.019	0.012	0.023	85.00 Lagging
Total constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.001	0.008	0.00	

Table 4.3 shows the summary of generation, loading, demand, and power factor for the normal load case. The motor load is 0.152 MW and the static load is 0.038 MW with 85% PF lagging. The power factor is quite low 83.47% lagging by demand and source. Apparent losses are 0.123 MW and 0.711 MVAR where

the apparent power is both power dissipated and absorbed by the system.

Table 4.4 Outputs on the bus bars

Bus Loading			
Bus ID Rated Voltage (KV)	Generation (MW)	Loading (MVA)	Current (Amp)
Bus 1 13.8kV	0.000	0.207	8.7
Bus 2 6kV	0.000	0.202	27.2
Bus 3 6kV	0.004	0.005	0.7
Bus 4 6kV	0.004	0.006	0.7
Bus 5 6kV	0.007	0.009	1.2
Bus 6 6kV	0.029	0.038	5.2
Bus 7 6kV	0.014	0.018	2.5
Bus 8 6kV	0.026	0.034	4.6
Bus 9 6kV	0.018	0.024	3.3
Bus 10 6kV	0.010	0.014	1.9
Bus 11 6kV	0.014	0.019	2.5
Bus 12 6kV	0.004	0.005	0.7
Bus 13 6kV	0.004	0.005	0.7
Bus 14 6kV	0.002	0.003	0.4
Bus 15 6kV	0.001	0.013	1.7
Bus 16 6kV	0.006	0.009	1.2
Bus 21 6kV	-0.000	0.202	27.2
Bus 23 11kV	0.000	0.205	10.9

Also for the normal load operation, there are 18 buses in total which are working in the system (Figure 4.5). Bus 1 and bus 23 have rated voltages as 13.8kV and 11 KV respectively. Bus 1 is connected to the grid and to the primary side of the transformer T1, whereas the secondary side of T1 transformer is connected to the primary side of T2 via bus 23. The secondary side of T2 transformer is connected to bus 21 which is then connected to cable and bus 2. Bus 2 is our load bus where all the loads meet to make the differential protection relay and the remaining buses have equal rated voltage of 6 KV. Busses 3 to 16 are connected to loads of 5.6 kVA, 6.1 kVA, 10.1 kVA, 42.6 kVA, 20.3 kVA, 38 kVA, 27kVA, 15.3 kVA, 20.6 kVA, 5.8 kVA, 3 kVA, 14 kVA, and 9.5 kVA respectively, so that the currents and power dissipations are almost different for every bus.

3. Case of 75% Load

   For this case, 75% of the load will be in service by using the power grid only where the system configuration is same as shown in Figure 3.4. Table 4.5 shows the summary of generation, loading, demand, and power factor. The motor load is 0.152 MW and the static load is 0.038 MW with 85% PF lagging and the power factor of sources and demand are 83.72% lagging.

Table 4.5 Summary of output in 75% load case

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.145	0.95	0.173	83.72 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.145	0.095	0.173	83.72 Lagging
Total Motor Load	0.128	0.079	0.150	85.00 Lagging
Total Static Load	0.016	0.010	0.019	85.00 Lagging
Total Constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.001	0.005	0.00	

Table 4.6 Bus Loading in 75% load case

Bus Loading			
Bus ID Rated Voltage (kV)	Generation (MW)	Demand (MVA)	Current (Amp)
Bus 1 13.8kV	0.000	0.173	7.3
Bus 2 6kV	0.000	0.170	22.8
Bus 5 6kV	0.007	0.009	1.2
Bus 6 6kV	0.029	0.038	5.2
Bus 7 6kV	0.014	0.018	2.5
Bus 8 6kV	0.026	0.034	4.6
Bus 9 6kV	0.018	0.024	3.3
Bus 10 6kV	0.010	0.014	1.9
Bus 11 6kV	0.014	0.019	2.5
Bus 15 6kV	0.001	0.013	1.7
Bus 21 6kV	-0.000	0.170	22.8
Bus 23 11kV	0.000	0.172	9.1

As given in Table 4.6, there are 8 buses in total which are working in the system. Bus 1 and bus 23 have rated voltages as 13.8kV and 11kV respectively, as bus 1 is connected to the grid and the primary side of transformer T1. The secondary side of T1 transformer is connected to primary side of T2 via bus 23; secondary side of T2 transformer is connected to bus 21 which is then connected to the cable and bus 2. Bus 2 is our load bus where all the loads meet to make the differential protection relay and the remaining buses have a rated voltage of 6kV. Buses 5 to 11 and bus 15 are connected to 10.1 kVA, 42.6 kVA, 20.3 kVA, 38 kVA, 27 kVA, 15.3 kVA, 20.6kVA, and 14 kVA respectively. Similar to the previous cases the current and power dissipation values are almost different for every bus due to the different load values.

4. Case of 50% Load

In this case, 50% of the load will be in service by using the power grid only. The configuration is same as shown in Figure 3.3. Table 4.7 shows the summary of generation, loading, demand, and power factor. The motor load is 0.078 MW and the static load is 0.010 MW with 85% PF lagging, the power factor of sources and demand are 83.72% lagging.

Table 4.7 Output of System in 50% Load Case

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.089	0.057	0.105	84.23 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.089	0.057	0.105	84.23 Lagging
Total Motor Load	0.078	0.048	0.092	85.00 Lagging
Total Static Load	0.010	0.006	0.012	85.00 Lagging
Total constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.000	0.002	0.00	

There are 8 buses in total working in the system. As before, bus 1 and bus 23 have rated voltage of 13.8kV and 11 KV respectively. Bus 1 is connected to the grid and the primary side of the transformer T1, where the secondary side of T1 transformer is connected to the primary side of T2 via bus 23. The secondary side of T2 transformer is connected to bus 21 which is then connected to cable and bus 2. Bus 2 is our load bus where all the loads meet to make the differential protection relay and the remaining buses have equal rated voltage of 6 KV. Bus 6, bus 7, bus 8, and bus 15 are connected to 42.6 kVA, 20.3 kVA, 38 kVA, and 14 kVA respectively, current and power dissipation values are again different for every bus. The summary bus values of this case is given in Table 4.8.

Table 4.8 Summary of Bus loading

Bus Loading			
Bus ID Rated Value (KV)	Generation (MW)	Loading (MVA)	Current (Amp)
Bus 1 13.8kV	0.000	0.105	4.4
Bus 2 6kV	0.000	0.104	13.8
Bus 6 6kV	0.029	0.039	5.1
Bus 7 6kV	0.014	0.018	2.4
Bus 8 6kV	0.026	0.034	4.6
Bus 15 6kV	0.001	0.013	1.7
Bus 21 6kV	-0.000	0.104	13.8
Bus 23 11kV	0.000	0.105	5.5

5. Case of 25% Load

   25% of load will be in service using the power grid only where the configuration is same as shown in Figure 3.2. Table 4.9 shows the summary. The motor load is 0.038 MW and the static load is 0.005 MW with 84.63% PF lagging, power factor of sources and demand are 84.63% lagging, hence, there is no difference between the 50% load and 25% load cases. The system operates perfectly with no sign of over voltages as the system is well protected by switchgears.

Table 4.9 Summary of Load in 25% Case

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.044	0.027	0.052	84.63 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.044	0.027	0.027	84.63 Lagging
Total Motor Load	0.038	0.048	0.024	85.00 Lagging
Total Static Load	0.005	0.003	0.006	85.00 Lagging
Total constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.000	0.000	0.00	

There are 6 buses in total which are working in the system. Bus 1 and bus 23 have rated voltage of 13.8kV and 11kV respectively. Bus 1 is connected to the grid and the primary side of the transformer T1, where the secondary side of T1 transformer is connected to primary side of T2 via bus 23. The secondary side of T2 transformer is connected to bus 21 which is connected to cable and bus 2. Bus 2 is our load bus where all the loads meet to make the differential protection relay and the remaining buses have equal rated voltage of 6 KV. Bus 6 and bus 15 are connected to the lump load of rating 42.6 kVA and 14 kVA respectively (Table 4.10).

Table 4.10 Bus Loading Summary in 25% Load case

Bus Loading			
Bus ID Rated Voltage (kV)	Generation (MW)	Demand (MVA)	Current (Amp)
Bus 1 13.8kV	0.000	0.053	2.2
Bus 2 6kV	0.000	0.051	68
Bus 6 6kV	0.018	0.039	5.1
Bus 15 6kV	0.006	0.013	1.7
Bus 21 6kV	-0.000	0.051	6.8
Bus 23 11kV	0.000	0.051	2.7

6. No Load Case

   In this case, there will be no load conected in the system but both sources (the generator and the power grid) will be used to analyze the voltages across the switchgear. As the switchgear bus voltages are independent of the generator or the grid, to find the maximum voltages on the switchgear, the grid or the generator has to be connected directly to the load without the transformer (Figure 4.6).

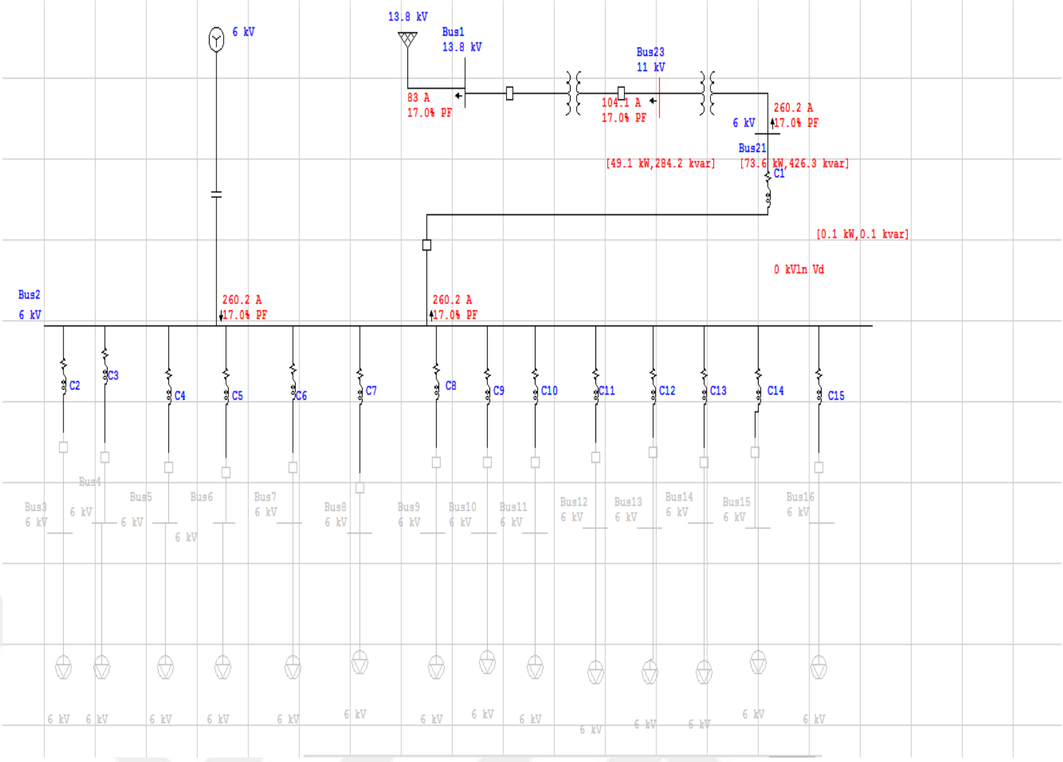


Figure 4.6 No Load operation

Table 4.11 shows the summary where both the motor load and the static load are zero with 17.02% PF lagging. The bus loading values are zero as there are no loads connected.

Table 4.11 Summary at No Load Case

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.000	0.000	0.000	17.02 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.000	0.000	0.000	17.02 Lagging
Total Motor Load	0.000	0.000	0.000	17.02 Lagging
Total Static Load	0.000	0.000	0.000	
Total constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.000	0.000	0.00	

7. Varying of cable length in normal load operation

Table 4.12 Summary of varying of cable length in normal load operation (100km)

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.214	0.135	0.253	84.54 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.214	0.135	0.253	84.54 Lagging
Total Motor Load	0.156	0.097	0.184	85.00 Lagging
Total Static Load	0.046	0.029	0.055	85.00 Lagging
Total constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.000	0.000	0.00	

Table 4.13 Summary of varying of cable length in normal load operation (50km)

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.212	0.134	0.25	84.42 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.212	0.134	0.251	84.42 Lagging
Total Motor Load	0.156	0.097	0.184	85.00 Lagging
Total Static Load	0.048	0.030	0.056	85.00 Lagging
Total constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.000	0.000	0.00	

Table 4.12 and Table 4.13 show's the variation of length and its impact on generation and loading.

8. Addition of Power Sources

Table 4.14 Summary of Addition of wind turbine in normal load operation

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.010	0.258	0.259	4 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.200	0.124	0.250	84.25 Lagging
Total Motor Load	0.156	0.097	0.184	85.00 Lagging
Total Static Load	0.049	0.031	0.058	85.00 Lagging
Total constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.000	0.000	0.00	

Above Table 4.14 shows the addition of wind turbine in system.

Table 4.15 Summary of Addition of two generator in normal load operation

	Generation (MW)	Loading (MVAR)	Demand (MVA)	PF (%)
Source(Swing Buses)	0.214	0.135	0.253	84.54 Lagging
Source(Non-Swing Buses)	0.00	0.00	0.00	
Total Demand	0.214	0.135	0.253	84.54 Lagging
Total Motor Load	0.156	0.097	0.184	85.00 Lagging
Total Static Load	0.046	0.029	0.055	85.00 Lagging
Total constant I Load	0.00	0.00	0.00	
Total Generic Load	0.00	0.00	0.00	
Apparent Losses	0.011	0.009	0.00	

Above Table 4.15 shows the addition of generators in system.

4.1.1 Comparison and Improvements

By comparing all the results described in the previous section, one observes that slight changes occur in the power factor of the system. If the power factor of the generated power is less than the rated power factor then the field winding is capable of matching the requirement. The generator capacity is actually based on the capability curve. The power flow from the generator for normal, maximum, and no load operations are available in the above tables. Large generators have to be designed for power factor of 0.85 lagging and relatively smaller ones are designed for a 0.8 power factor.

In normal mode operation (all the generators and transformers are working) the grid connected to the transformer is in swing mode and the generator is in PF control mode with PF setting of 0.85 with 13.6kV and 213kW. In this case, the load flow results show that the power exported to the grid has a power factor of 83.5%. If it would be lower than 0.8, the rated power factor of the generator should be increased.

In maximum load operation (grid is not working) the generator is working in swing mode and it delivers power to the system at 85% power factor. In no load case, the generator and the grid are both working in swing mode with no load, a power factor of 17.5% is observed. In 25%, 50%, and 75% of load, there are no sign of over voltages as the system is working properly under the protection of switchgears whereas slight changes are observed in the apparent losses and power factors.

If voltage of the power grid is less than the generator voltage, then the generator reduces the amount of reactive power, and thus the power factor will get lower than 0.8, the rated value of the generator as displayed in Figure 4.7. This problem will be solved by increasing the taps of the transformers, e.g. a 2.5% tap is added to the transformer T1. Figure 4.8 shows that because of this tapping of the transformer, the power factor is improved drastically to 83.5%.

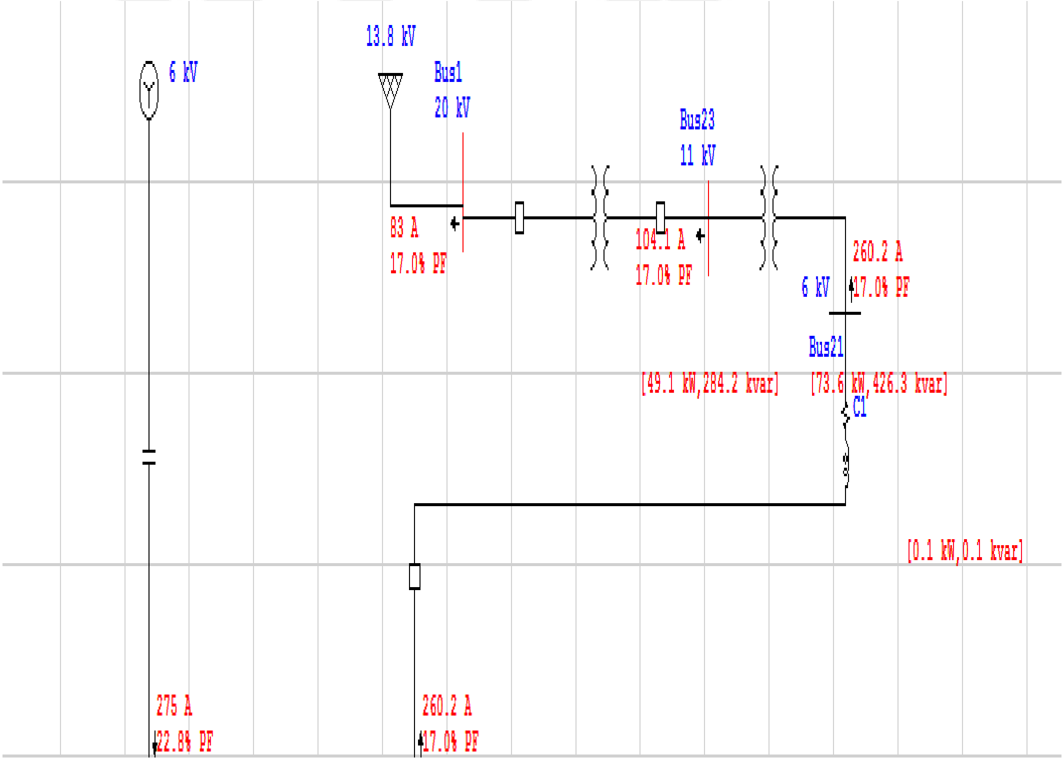


Figure 4.7 Output before tapping of transformer T1: PF is 17.5%

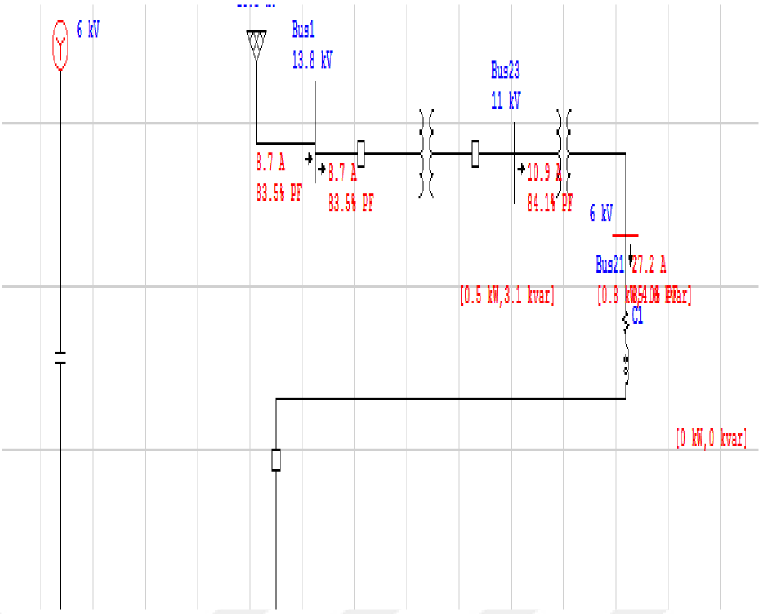


Figure 4.8 Output with 2.5% tap in transformer T1: PF is 83.5%

Percentage of the bus loading is up to 80% during the feed stage and up to 90% in engineering stage. The current through the bus is usually calculated by the apparent power and voltage across the switchgear bus. The current ratings are adopted from the IEC standard current ratings. This model consists of a static load (constant impedance load) and a motor load (constant kVA load) where the motor load doesn't vary with voltage. Motor control centre (MCC) bus takes 100% of the motor load. If the MCC bus operates under 95% of the bus voltage then current flow through MCC will be 5% more compared to the MCC bus operating under 100% static load. If the distributive panel (DB) is operating at 105% voltage then the current drawn will exceed 5% of its rated value. So, one thing has to be kept in mind: by the time of designing, in MCC and DB, a 5% margin has to exist. The system should be designed in terms of the 75% load in feed stage, and 85% during engineering stage where the standard values are 80% and 90% respectively. As switchgears feed the power to the motor and static load, because of voltage regulation, both loads compensate their increase in current withdraw. The margin values required can be expressed as follows:

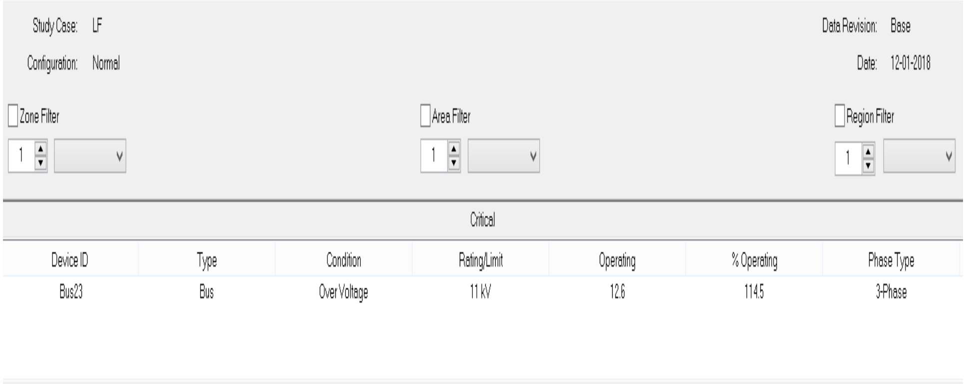
$$\%Margin = \%M\left(\frac{100}{\%V} - \frac{\%V}{100}\right) + \%V - 100 \tag{4.1}$$

where %M is the percentage motor load and %V is the voltage.

4.1.2 Error Alerts During Load Flow Analysis

During the load flow analysis, two types of alerts have been observed: over voltages and under voltages, which are discussed in the following sections.

- Load flow analysis with an improvement to overcome the problem of under voltages
  When reactive power is available in the load base, voltage level may go down and the chronic under voltages produced can cause severe damage especially in the case of motors: the motor cannot run properly under low voltage which causes the motor winding to become hot. There are ways to solve this problem e.g. placement of capacitor banks in shunt around the feeder. In our system, whenever it is running under normal load conditions (the generator is running together with the power grid) under voltages do not occur. However, in other cases such as 25%, 50%, and 75% load, the simulator immediately shows that feeders are under voltages that causes an increase in losses as compared to other cases.
- Load flow analysis with an improvement to overcome the problem of over voltages
  This is one of the biggest problem of the industry. There are external or internal causes of over voltages. Internal causes will be discussed for our system as no external cause is simulated. An over voltage is caused when the switching operation is carried out under normal load conditions, (all the generators and transformers are working). Due to the Ferranti effect, whenever an unloaded line is charged, there is an increase of voltages at the receiving end, thus an over voltage will occur. This type of alert appeared when the generator is used parallel with the power grid in normal load case. Increasing the secondary side tap of the transformer T1, over voltages vanished as it was due to the voltages on the bus 23 as shown in Figure 4.9.



Study Case: LF

Configuration: Normal

Data Revision: Base

Date: 12-01-2018

☐ Zone Filter 1

☐ Area Filter 1

☐ Region Filter 1

Critical

Device ID	Type	Condition	Rating/Limit	Operating	% Operating	Phase Type
Bus23	Bus	Over Voltage	11 kV	12.6	114.5	3-Phase

Figure 4.9 Error alert of over voltages during load flow

4.2 Short Circuit Analysis and Results

In this section, short circuit analysis results of power system simulations will be utilized where factors will be highlighted that have to be considered in designing of electrical equipments. Bus bars of switchgears are designed to withstand the thermal and electromagnetic effects. The electromagnetic effects are caused by the electromagnetic peak force of conductors due to the three phase fault currents in the system F_{m3}. Moreover, peak forces between conductors are produced due to the LL fault current F_{m2}. The stress due to the bending forces $\sigma_{m,d}$, F_{m3}, F_{m2}, and $\sigma_{m,d}$ are calculated based on the standards (Yusop et al., 2011). Thermal effects of bus bars depend on the material, area of conductor, thermal equivalent short circuit current I_{th} and duration of the short circuit current where I_{th} depends on I_k and I_k is available in the results.

Circuit breakers are designed for short circuit breaking current I_{sc}, short circuit making capacity I_m, and short time withstand current I_w for duration of 1 sec or 3 sec. I_m for HV circuit breakers is designed as 2.5 times of I_w. I_m shall be greater than or equal to I_p of the maximum short circuit current.

I_{sc} of the circuit breaker includes DC and AC components. The AC component of I_{sc} is equal to I_w. The DC component depends on the operating time of the circuit breaker T_{op}, time constant, and time period of the half cycle. T_{op} is usually provided by the manufacturer. Generally, circuit breakers are designed and tested for T_{op} of 40-60ms and for a time constant of 45ms. The simulation report gives the angle between the fault current and the voltage. Time constant of the fault current can be calculated based on the angle. If the time constant of fault current exceeds 45ms then the “I x t” of fault current shall not exceed the rated “I x t” of the circuit breaker where “I x t” is the product of peak value of the last short circuit current loop (I) before breaking and the duration of last short circuit current loop (t).

Generators are not designed for maximum available fault current, however the generator terminal box is designed to withstand the fault current. Transformers are designed to withstand the fault current. The fault current of a transformer is calculated by following the modifications in the system:

- Motor load will be taken out of service.
- Maximum short circuit MVA will be chosen at primary side of the transformer.
- Low impedance path will be chosen between the primary side of transformer and source.

Transformers are designed to withstand the thermal and electromagnetic effect. Thermal effects are based on the duration of fault current (which is 2 sec) and on I_k of the three phase fault currents. The electromagnetic effect consists of the radial tensile, radial bursting force, internal axial compression force, and axial imbalance force due to tapping.

While performing short circuit analysis, some faults should be introduced in the system like on bus1, bus2, bus 5, 6, 7 and a surge on bus 2 which is our main bus. In the following, the results will be discussed for different cases of load.

1. Case of 75% load

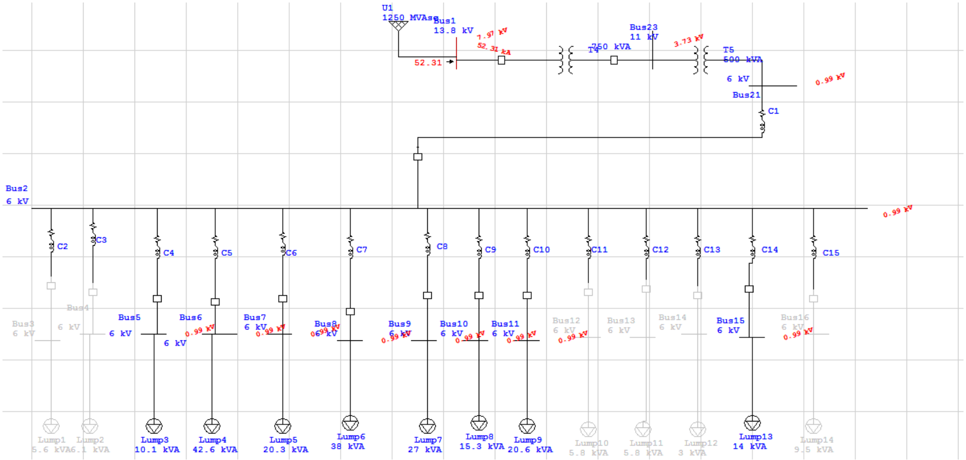


Figure 4.10 Fault in main bus 1 with 75% of load

Figure 4.10 shows the fault in bus 1 which is connected to the power grid. By running a short circuit analysis, it represents the faulty bus highlighting it in red colour. The results of introducing the fault in bus 1 are given in Tables 4.16, 4.17, and 4.18.

Table 4.16 LG Fault on Bus1 at 75% Load

Line to Ground Faults (Current Values KA)						
Bus ID	Ia	Ib	Ic	I1	I2	I3
Bus 1	52.310	0.00	0.00	17.437	17.437	17.437
Bus 23	0.014	0.007	0.007	0.007	0.007	0.00
U1	52.96	0.007	0.007	17.430	17.430	17.437

Table 4.16 shows the different values of currents while introducing Line to ground fault in bus 1.

Table 4.17 LL Fault on Bus1 at 75% Load

Line to Line Faults (Current Values KA)						
Bus ID	Ia	Ib	Ic	I1	I2	I3
Bus 1	0.000	45.307	45.307	26.158	26.158	0.00
Bus 23	0.000	0.018	0.018	0.010	0.010	0.00
U1	0.000	45.290	45.290	26.148	26.148	0.00

Table 4.17 shows the different values of currents while introducing Line to Line fault in bus 1.

Table 4.18 LLG Fault on Bus1 at 75% Load

Line to Line to Ground Faults (Current Values KA)						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 1	0.0	152.9	32.9	17.441	17.434	0.00
Bus 23	-81.4	177.8	19.5	0.007	0.007	0.00
U1	98.6	152.9	32.9	17.434	17.434	0.00

Table 4.17 shows the different values of currents while introducing Line to Line to ground fault in bus 1.

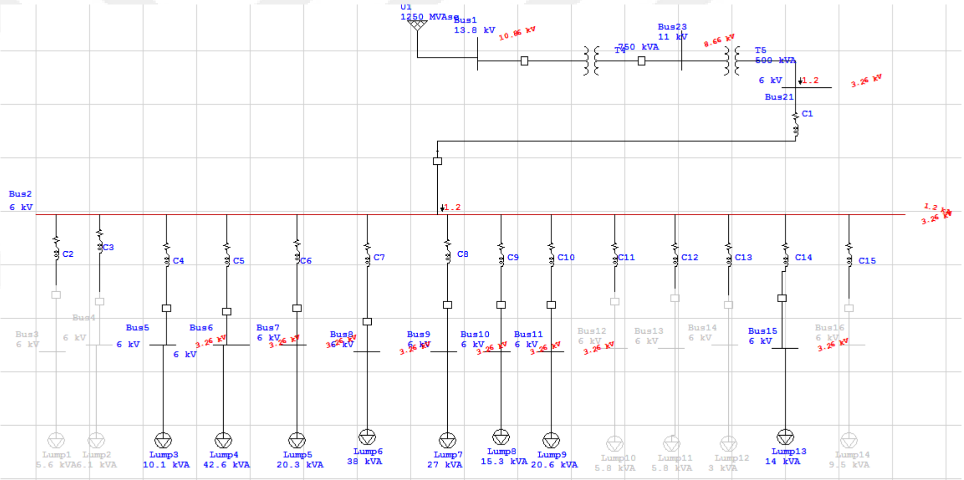


Figure 4.11 Fault in main bus 2 with 75% of load

Figure 4.11 shows the fault in bus 2 which is the main bus; on this bus all the lump loads are connected via cable and CB. Similarly, the results of this fault are given in Tables 4.19, 4.20, and 4.21.

Table 4.19 LG Fault on Bus 2 at 75% Load

Line to Ground Faults (Current Values KA)						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 2	1.205	0.00	0.00	0.402	0.420	0.402
Bus 5	0.004	0.002	0.002	0.002	0.002	0.00
Bus 6	0.016	0.008	0.008	0.008	0.008	0.00
Bus 7	0.008	0.004	0.004	0.004	0.004	0.00
Bus 8	0.014	0.007	0.007	0.007	0.007	0.00
Bus 9	0.010	0.005	0.005	0.005	0.005	0.00
Bus 10	0.006	0.003	0.003	0.003	0.003	0.00
Bus 11	0.008	0.004	0.004	0.004	0.004	0.00
Bus 12	0.002	0.001	0.001	0.001	0.001	0.00
Bus 15	0.005	0.0039	0.0039	0.003	0.003	0.00
Bus 21	1.133	0.036	0.036	0.366	0.366	0.402

Table 4.19 shows the different values of currents while introducing Line to ground fault in bus 2.

Table 4.20 LL Fault on Bus 2 at 75% Load

Line to Line Faults (Current Values KA)						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 2	0.000	0.924	0.924	0.534	0.534	0.00
Bus 5	0.000	0.004	0.004	0.002	0.002	0.00
Bus 6	0.000	0.018	0.018	0.011	0.011	0.00
Bus 7	0.000	0.009	0.009	0.005	0.005	0.00
Bus 8	0.000	0.016	0.016	0.009	0.009	0.00
Bus 9	0.000	0.0012	0.012	0.007	0.007	0.00
Bus 10	0.000	0.007	0.007	0.004	0.004	0.00
Bus 11	0.000	0.009	0.009	0.005	0.005	0.00
Bus 12	0.000	0.002	0.002	0.001	0.001	0.00
Bus 15	0.000	0.006	0.006	0.003	0.003	0.00
Bus 21	0.000	0.814	0.814	0.486	0.486	0.000

Table 4.20 shows the different values of currents while introducing Line to Line fault in bus 2.

Table 4.21 LLG Fault on Bus 2 at 75% Load

Line to Line to Ground Faults (Current Values KA)						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 2	0.000	152.9	46.5	0.303	0.461	0.00
Bus 5	-81.4	174.5	22.5	0.001	0.000	0.00
Bus 6	-81.4	174.5	22.5	0.006	0.000	0.00
Bus 7	-81.4	174.5	22.5	0.003	0.000	0.00
Bus 12	-81.4	174.5	22.5	0.001	0.000	0.00
Bus 15	-81.4	174.5	22.5	0.002	0.000	0.00
Bus 21	98.6	151.2	48.4	0.276	0.461	0.000

Table 4.21 shows the different values of currents while introducing Line to line to ground fault in bus 2.

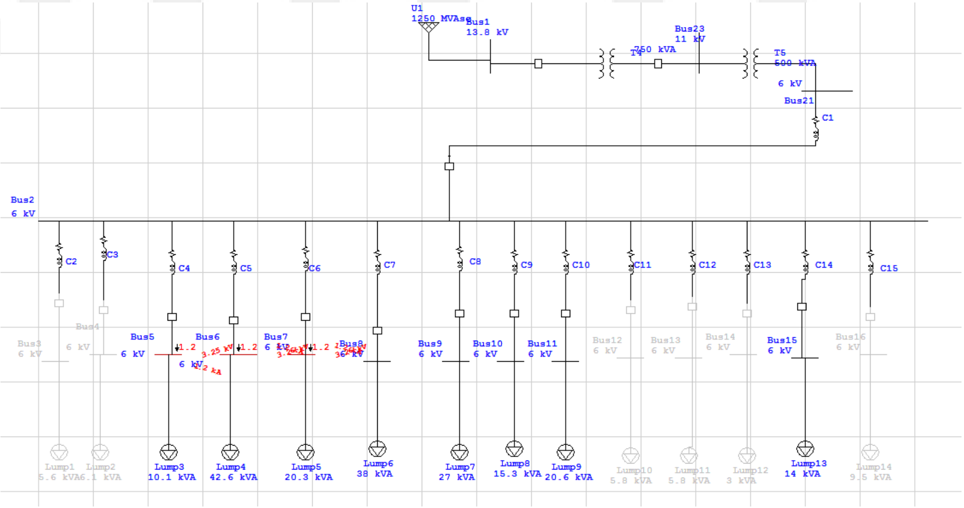


Figure 4.12 Fault in bus 5, 6 & 7 with 75% of load

Figure 4.12 shows the fault in bus 1 which is connected to the power grid. By running a short circuit analysis, it represents the faulty bus highlighting it in red colour. The results of introducing the fault in bus 5, 6 and 7 are given in Tables 4.22, 4.23, and 4.24.

Table 4.22 LG Fault on Bus 5,6 &7 at 75% Load

Line to Ground Faults (Current Values KA)						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 5	1.204	0.000	0.00	0.401	0.401	0.401
Bus 2	1.20	0.002	0.002	0.399	0.339	0.401
Lump2	0.004	0.002	0.002	0.002	0.002	0.000
Bus 6	1.205	0.00	0.00	0.402	0.402	0.402
Bus 2	1.189	0.008	0.008	0.394	0.394	0.402
Lump3	0.016	0.008	0.008	0.008	0.008	0.000
Bus 7	-81.4	174.5	22.5	0.004	0.000	0.00
Bus 2	-81.4	174.5	22.5	0.002	0.000	0.00
Lump4	0.016	0.008	0.008	0.008	0.008	0.000

Table 4.21 shows the different values of currents while introducing Line ground fault in bus 5, 6 and 7.

Table 4.23 LL Fault on Bus 5,6 &7 at 75% Load

Line to Line Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 5	0.000	0.924	0.924	0.534	0.534	0.000
Bus 6	0.000	0.924	0.924	0.523	0.523	0.000
Bus 7	0.000	0.924	0.924	0.533	0.5332	0.000

Table 4.23 shows the different values of currents while introducing Line to line fault in bus 5, 6 and 7.

Table 4.24 LLG Fault on Bus 5,6 &7 at 75% Load

Line to Line to Ground Faults						
Bus 5	0.00	153.1	46.7	0.303	0.461	0.000
Bus 6	0.0	153.0	46.6	0.303	0.461	0.401
Bus 7	0.004	153	46.6	0.303	0.461	0.000

Table 4.24 shows the different values of currents while introducing Line to line fault in bus 5, 6 and 7.

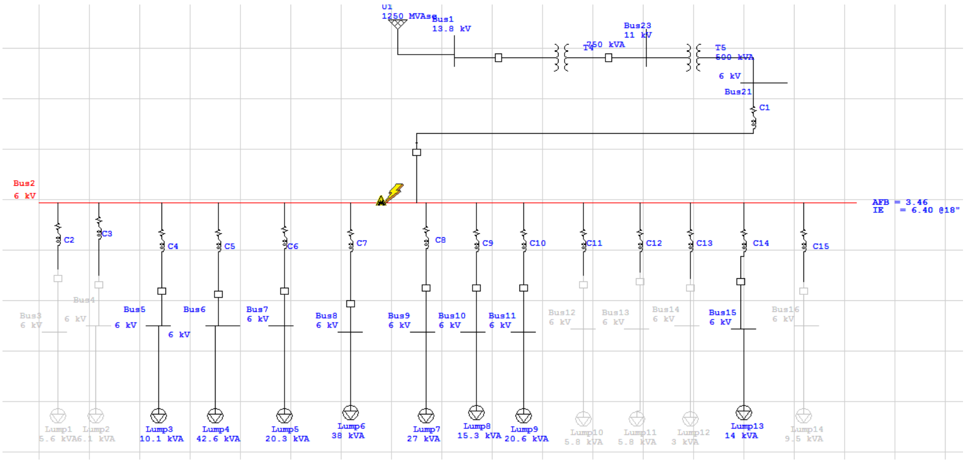


Figure 4.13 Arc flash in main bus 2 with 75% of load

Figure 4.13 shows the fault in main bus 2 which is connected to the power grid. By running a short circuit analysis, it represents the faulty bus highlighting it in red colour. The results of introducing the arc flash fault in bus 2 are given in Table 4.25.

Table 4.25 Summary of Arc Flash Hazard Calculations 75% Load

Arc flashing							
Faulted Bus	Bolted Fault Curent	Fault Current (KA)	Trip Device	FCT	Arc Flash boundary	Incident Energy (cal/cm^2)	Energy Level
Bus 2 6 KV	13	1.065	13	3.5	6.4	18	Level 2

Table 4.24 shows the energy level, incident Energy, trip devices e.t.c which represents the system capacity to bear surges.

2. In 50% load case

   While performing short circuit analysis, some faults should be introduced in the system like on bus1, bus2, bus 5,6 & 7 and surge on bus 2 (bus 2 is our main bus).

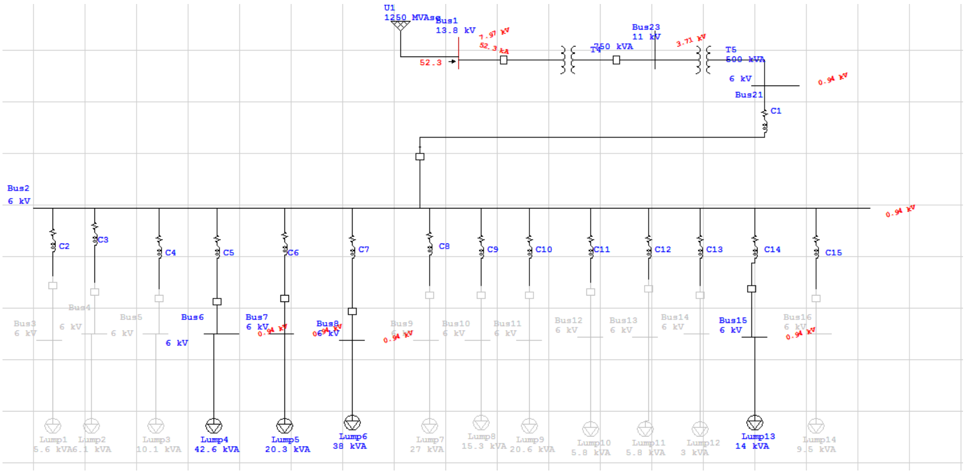


Figure 4.14 Fault in main bus 1 with 50% of load

Figure 4.14 shows the fault in bus 1 which is connected to the power grid with 50% of load. By running a short circuit analysis, it represents the faulty bus highlighting it in red colour. The results of introducing the fault in bus 1 are given in Tables 4.26, 4.27, and 4.28.

Table 4.26 LG Fault on Bus 1 at 50% Load

Line to Ground Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 1	52.305	0.00	0.000	17.435	17.435	17.435

Table 4.26 shows the different values of currents while introducing Line to ground fault in bus 1.

Table 4.27 LL Fault on Bus 1 at 50% Load

Line to Line Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 1	0.000	45.301	45.301	26.154	26.154	0.000

Table 4.27 shows the different values of currents while introducing Line to Line fault in bus 1.

Table 4.28 LLG Fault on Bus 1 at 50% Load

Line to Line to Ground Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 1	0.000	152.9	32.9	17.438	17.433	0.000

Table 4.28 shows the different values of currents while introducing Line to Line to ground fault in bus 1.

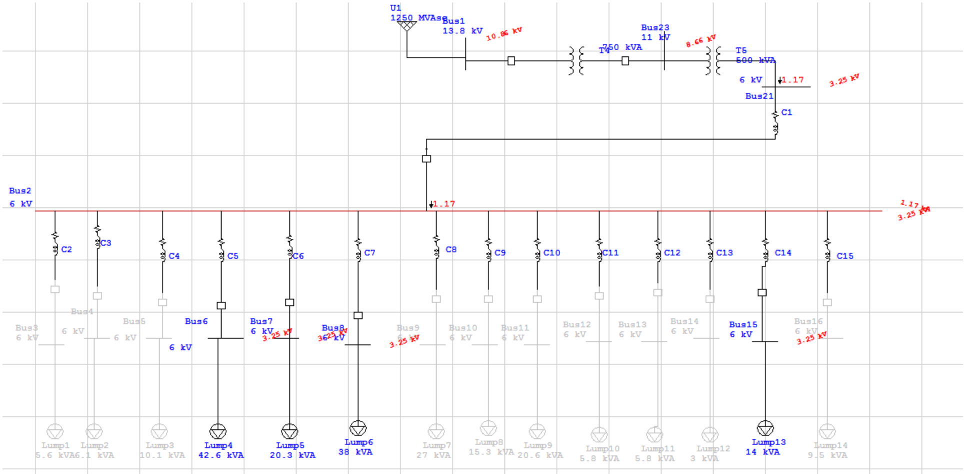


Figure 4.15 Fault in main bus 2 with 50% of load

Figure 4.15 shows the fault in bus 1 which is connected to the power grid with 50% of load. By running a short circuit analysis, it represents the faulty bus highlighting it in red colour. The results of introducing the fault in bus 1 are given in Tables 4.29, 4.30, and 4.31.

Table 4.29 LG Fault on Bus 2 at 50% Load

Line to ground Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 2	0.00	0.891	0.891	0.514	0.514	0.00

Table 4.29 shows the different values of currents while introducing Line to ground fault in bus 2.

Table 4.30 LLG Fault on Bus 2 at 50% Load

Line to Line to Ground Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 2	0.00	152.3	47.1	0.287	0.454	0.00

Table 4.30 shows the different values of currents while introducing Line to Line to ground fault in bus 2.

Table 4.31 LL Fault on Bus 2 at 50% Load

Line to Line Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 2	1.1172	0.00	0.00	0.391	0.391	0.391

Table 4.31 shows the different values of currents while introducing Line to Line fault in bus 2.

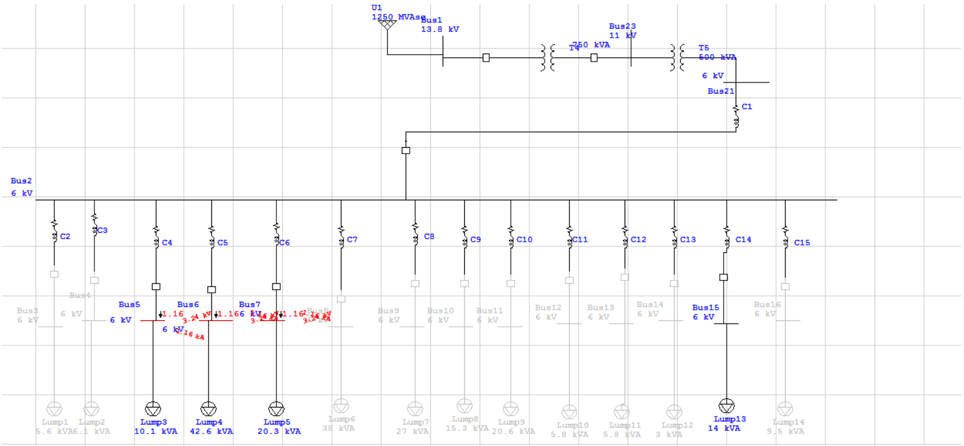


Figure 4.16 Fault in main bus 5, 6 & 7 with 50% of load

Figure 4.16 shows the fault in bus 5, 6 and 7 which is connected to the power grid with 50% of Load. By running a short circuit analysis, it represents the faulty bus highlighting it in red colour. The results of introducing the fault in bus 1 are given in Tables 4.32, 4.33, and 4.34.

Table 4.32 LG Fault on Bus 6,7 & 8 at 50% Load

Line to ground Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 6	1.171	0.00	0.00	0.390	0.390	0.390
Bus 7	1.171	0.00	0.00	0.390	0.390	0.391
Bus 8	1.171	0.00	0.00	0.390	0.390	0.390

Table 4.32 shows the different values of currents while introducing Line to ground fault in bus 5, 6 and 7.

Table 4.33 LL Fault on Bus 6,7 & 8 at 50% Load

Line to Line Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 6	0.00	0.890	0.890	0.514	0.514	0.00
Bus 7	0.00	0.890	0.890	0.514	0.514	0.00
Bus 8	0.0	0.890	0.890	0.514	0.514	0.00

Table 4.33 shows the different values of currents while introducing line to line fault in bus 5, 6 and 7.

Table 4.34 LLG Fault on Bus 6,7 & 8 at 50% Load

Line to Line to Ground Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 6	0.00	152.4	47.2	0.287	0.454	0.00
Bus 7	0.00	152.5	47.2	0.287	0.453	0.00
Bus 8	0.0	152.5	0.890	0.287	0.453	0.00

Table 4.34 shows the different values of currents while introducing Line to ground fault in bus 5, 6 and 7.

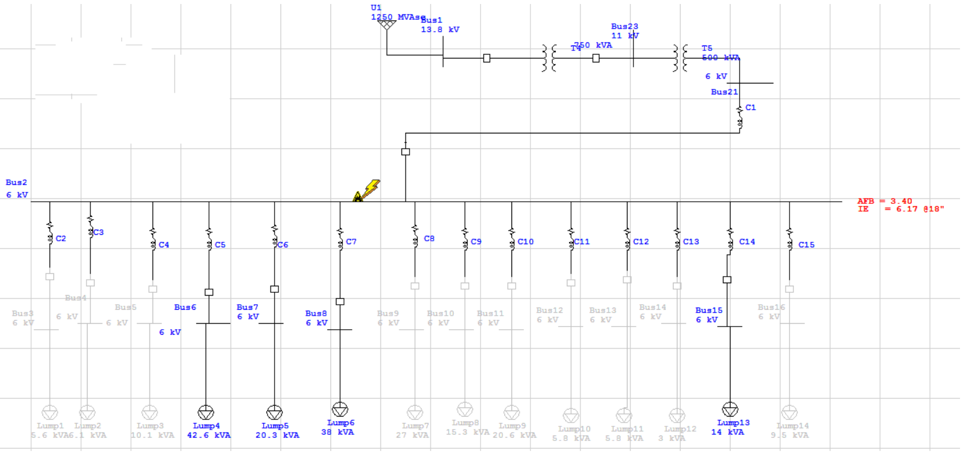


Figure 4.17 Arc flash in main bus 2 with 50% of load

Figure 4.17 shows the fault in main bus 2 which is connected to the power grid. By running a short circuit analysis, it represents the faulty bus highlighting it in red colour. The results of introducing the arc flash fault in bus 2 are given in Table 4.35.

Table 4.35 Summary of Arc Flash Hazard Calculations on 50% Load

Arc flashing							
Faulted Bus	Bolted Fault Curent	Fault Current (KA)	Trip Device	FCT	Arc Flash boundary	Incident Energy (cal/cm^2)	Energy Level
Bus 2 6 KV	13	1.028	13	3.4	6.2	18	Level 2

Table 4.35 shows the energy level, incident Energy, trip devices e.t.c which represents the system capacity to bear surges.

3. In 25% load case

   While performing short circuit analysis, some faults should be introduced in the system like on bus1, bus2, bus 5,6 & 7 and surge on bus 2 (bus 2 is our main bus).

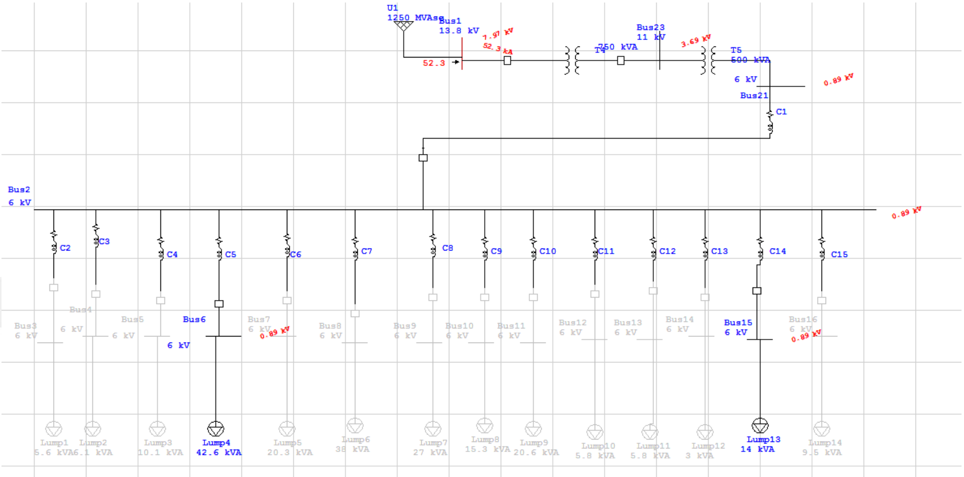


Figure 4.18 Fault in main bus 1 with 25% of load

Figure 4.18 shows the fault in bus 1 which is connected to the power grid. By running a short circuit analysis, it represents the faulty bus highlighting it in red colour. The results of introducing the fault in bus 1 are given in Tables 4.36.

Table 4.36 LG Fault on Bus 1 at 25% Load

Line to Ground Faults						
Bus ID	Ia	Ib	Ic	I1	I2	I0
Bus 6	52.30	0.00	47.2	17.43	17.43	17.43
Bus 23	0.004	0.002	0.002	0.002	0.002	0.00
U1	52.96	0.002	0.002	17.431	17.431	17.433

Table 4.34 shows the different values of currents while introducing Line to ground fault in bus 1.

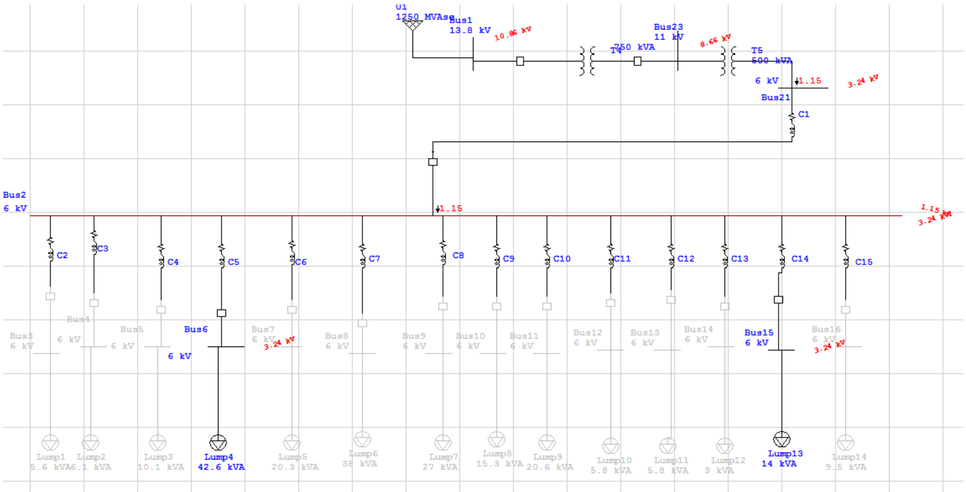


Figure 4.19 Fault in main bus 2 with 25% of load

Figure 4.19 shows the different values of currents while introducing Line to ground fault in bus 2.

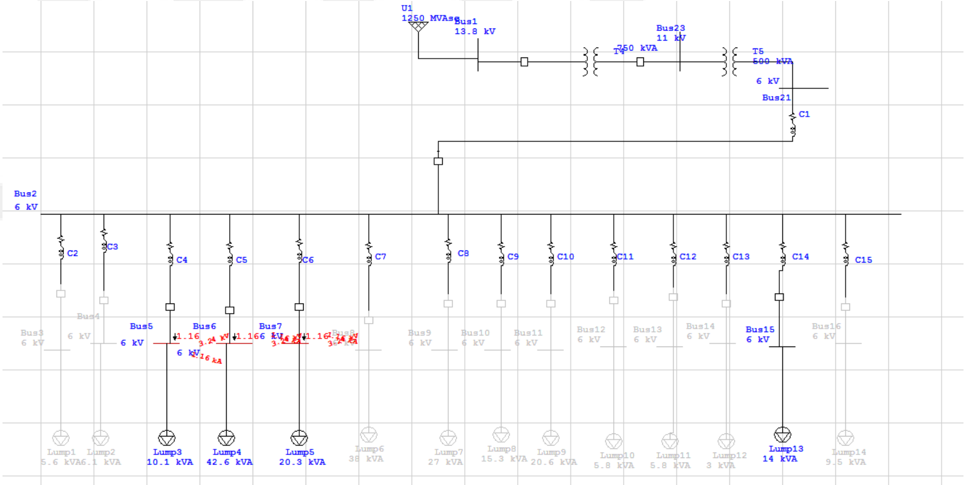


Figure 4.20 Fault in main bus 5, 6 & 7 with 25% of load

Figure 4.20 shows the different values of currents while introducing Line to ground fault in bus 5, 6 and 7.

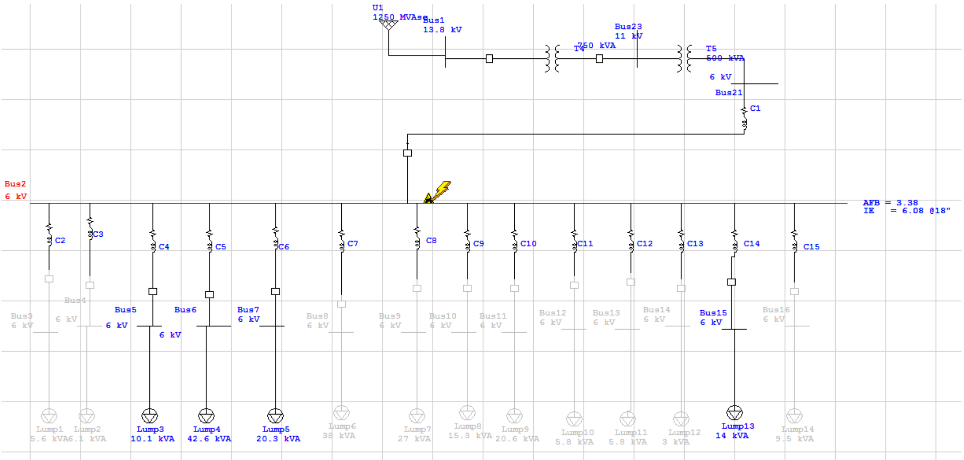


Figure 4.21 Arc flash in main bus 2 with 25% of load

Figure 4.21 shows the arc flash test, when surges are dropped on the main bus.

Table 4.37 Summary of Arc Flash Hazard Calculations on 25% Load

Arc flashing							
Faulted Bus	Bolted Fault Curent	Fault Current (KA)	Trip Device	FCT	Arc Flash boundary	Incident Energy (cal/cm^2)	Energy Level
Bus 2 6 KV	13	1.000	13	3.3	6.0	18	Level 2

Table 4.37 shows the triping of device, energy level, and fault current that are produced after the surge.

5. CONCLUSION

Load flow analysis and short circuit analysis are very important in designing of electrical power systems. In this Thesis, those two types of analyses are performed to investigate the system behaviour and to make some suggestions for improvement. Short circuit analysis is required to ensure that the equipments are protected by protective devices such as circuit breakers and fuses having some interrupt ratings. If the current exceeds the interrupting rating, the result will be destructive, so circuit breakers and fuses reduce the risk and avoid catastrophic losses. Some hypothetical situations are simulated to check the behaviour of the electrical power system on different loads. Varying amounts of load is a common situation in today's environment which will impact the whole system in positive and in negative manner. Load flow studies determine if system voltages remain within specified limits under normal or emergency operating conditions, and whether equipment such as transformers and conductors are overloaded. Load flow analysis is the most important and essential approach to investigate problems in power system operating and planning. Based on a specified generating state and transmission network structure, load flow analysis solves the steady operation state with node voltages and branch power flow in the power system. Previous work was done in the design of electrical systems by using full load of the system and no load of the system. In this Thesis, a fine variation of the load is performed in load flow and short circuit analysis to analyze the system behaviour with the arc flash test on different bus bars to check the capability of the system to withstand those adverse effects.

The main contribution of this Thesis is that an electrical system is designed using a simulation environment, load flow and short circuit analysis are performed by variations of the load. Meanwhile multiple design parameters are discussed in detail and some problems are encountered like power factor correction, under voltages and over voltages. By this, efficiency and capability of the system are tested, and under some conditions, the errors are highlighted. Arc flash run test is also achieved by which one can know about the incident energy of the potential arc flash which is usually caused by light or heat produced by low impedance connection through air to ground or with another voltage in the electrical system.

This work can be used as a framework for designing of electrical systems to achieve different results by introducing different problems and faults in the system. Most of the abovementioned errors and the debugging of the error are explained in details.

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APPENDIX A: Equations

$$I_i = \sum_{j=1}^{n} Y_(ij) V_j \tag{A.1}$$

$$I_i = \sum_{j=i}^{n} |V_{ij}||V_i| < \theta_{ij} + \delta_j \tag{A.2}$$

$$I_i = \frac{P_i - jQ_i}{V_i} \tag{A.3}$$

$$P_i - jQ_i = |V_i| < -\sum_{j=i}^{n} |V_{ij}||V_i| < \theta_{ij} + \delta_j \tag{A.4}$$

$$P_i = \sum_{j=1}^{n} |V_i||V_j||V_{ij}| cos(\theta_{ij} - \delta_i + \delta_j) \tag{A.5}$$

$$Zsc = \sqrt{R^2 + X^2} \tag{A.6}$$

$$cos\alpha = \frac{R}{\sqrt{R^2 + X^2}} \tag{A.7}$$

$$R = \rho \frac{L}{A} \tag{A.8}$$

$$V_3\phi = \frac{\sqrt{3} I (R_c cos\phi + X_c sin\phi) L}{1000} \tag{A.9}$$

$$V_1\phi = \frac{2I (R_c cos\phi + X_c sin\phi) L}{1000} \tag{A.10}$$

$$A = \frac{\sqrt{I^2}}{k} \tag{A.11}$$

$$k = 226 \sqrt{\ln\left(1 + \frac{\theta_f - \theta_i}{234.5 + \theta_i}\right)} \tag{A.12}$$

$$A = \frac{I\sqrt{t}}{K} \tag{A.13}$$

$$Ns = \frac{120f}{P} \tag{A.14}$$

$$s = \frac{N_s - N}{Ns} \tag{A.15}$$

$$\%Margin = \%M\left(\frac{100}{\%V} - \frac{\%V}{100}\right) + \%V - 100 \tag{A.16}$$