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Faculté des Sciences et de la Technologie

N° d’ordre M…/GE/2023

MEMOIRE DE FIN D’ETUDES DE

MASTER ACADEMIQUE

Filière : Génie Electrique

Spécialité : Electrotechnique Industriel

Thème

STABILITY OF POWER SYSTEM WITH DER INTEGRATION

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Année Universitaire : 2022 / 2023

ACKNOWLEDGEMENT

First, I thank Allah for giving me the power and determination to conclude my thesis successfully.

I would like to thank my supervisor, Mme. GHOMRI LEILA, for his assistance, ideas, and feedback during the process of doing this dissertation. Without his guidance, this dissertation would not be completed on time. and a special thanks to my discussion committee for accepting them to discuss my thesis.

Each of us has people who light up his life, in the forefront of them is my wonderful father, which is the main reason for completing this thesis, he is always encouraging me to finish it, and my loving mother who Illuminates my way of science and knowledge since my childhood.

Finally, yet importantly, there is someone I need to mention especially, my friend, Dr Mosbah, for his support and help throughout the process.

Last but not least, I would like to thank everyone who contributed to the success of this dissertation.

Dedication

I dedicate this research to my parents, to those who are not matched by anyone in the universe, to whom God has commanded us to honor, and to those who have made a great deal and have given what cannot be returned.

To my dear brothers and sisters, to all my friends.

To whom we will not forget ever our brave prisoners in the prisons of the occupation, also to those who sacrificed for the sake of Palestine.

Abstract

With the increasing demand for electrical energy, we are currently seeking to improve the stability of electrical networks by integrating renewable energy systems, which play an important role in reducing global warming. This work presented a simulation of an electric network with the integration of renewable energy with a transient stability analysis performed by the Etap program. The power flow, short circuit, and transient stability were analyzed.

Keywords: power system, transient stability, ETAP, PV system, wind turbine generator, power flow.

Résumé

Avec la demande croissante en énergie électrique, nous cherchons actuellement à améliorer la stabilité des réseaux électriques en intégrant des systèmes d'énergies renouvelables, qui jouent un rôle important dans la réduction du réchauffement climatique. Ce travail a présenté une simulation d'un réseau électrique avec l'intégration des énergies renouvelables avec une analyse de stabilité transitoire réalisée par le programme Etap. Le flux de puissance, le court-circuit et la stabilité transitoire ont été analysés.

Mots-clés : système électrique, stabilité transitoire, ETAP, système PV, éolienne, flux de puissance.

ملخص

مع تزايد الطلب على الطاقة الكهربائية ، نسعى حاليا إلى تحسين استقرار الشبكات الكهربائية من خلال دمج أنظمة الطاقة المتجددة ، والتي تلعب دورا مهما في الحد من ظاهرة الاحتباس الحراري. قدم هذا العمل محاكاة لشبكة كهربائية مع دمج الطاقة المتجددة مع تحليل الاستقرار العابر الذي أجراه برنامج إيتاب. تم تحليل تدفق الطاقة ، ماس كهربائى ، والاستقرار العابر

الكلمات المفتاحية: نظام الطاقة ، الاستقرار العابر ، إيتاب ، النظام الكهروضوئي ، مولد توربينات الرياح ، تدفق الطاقه

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Introduction:

Since the beginning of the century, global energy consumption has been growing very strongly in all regions. It seems that energy consumption will continue to increase, under the effect of economic growth on the one hand, and the increase in electricity consumption per inhabitant on the other hand, whatever the scenarios considered.

The power system, also known as the electric grid, is immensely important for society and the economy. It facilitates electricity generation, transmission, and distribution to meet the energy needs of homes, businesses, and industries. A reliable power system ensures the availability of electricity for essential services like healthcare, communication, and public safety. It supports economic growth by powering industries, enabling productivity, and attracting investments. Efficient power systems promote sustainability by integrating renewable energy sources and reducing environmental impact.

Renewable energy sources are of paramount importance for a sustainable future. They provide a clean and abundant alternative to fossil fuels, reducing greenhouse gas emissions and combating climate change. By harnessing the power of wind and solar and we can decrease our dependence on finite resources and mitigate environmental degradation. Renewable energy also promotes energy security, as it diversifies our energy mix and reduces reliance on imported fuels. Investing in renewable energy fosters innovation, job creation, and economic growth while paving the way for a greener and more resilient world.

The stability of a power system is crucial for ensuring a reliable and uninterrupted electricity supply. It prevents blackouts, equipment damage, and disruptions to critical services. A stable power system supports economic growth by providing a consistent and efficient energy source for industries, businesses, and households. It enables the integration of renewable energy sources, ensuring a smooth transition to a sustainable future. Power system stability also enhances grid resilience, allowing for quick recovery from disturbances and natural disasters. Overall, a stable power system is essential for the functioning and well-being of modern societies. This study was selected for a number of reasons. First, subjective reasons are based on a desire to choose this topic. Second: For objective reasons that require keeping pace with developments in scientific research

Problem statement: The problem of this study is the study of the transient stability of the system after the integration of renewable energy sources on the system and the study of the potential effects by ETAP software

The first chapter presents the basic concepts of power systems, such as the basic structure of power distribution stations, and the basic concepts of power flow, as well as the faults that occur in the system.

The second chapter presents the concepts of transient stability, their classifications, and some equations related to transient stability.

The third chapter presents the Simulated results of a network before the integration of renewable energy systems, was presented using the ETAP program.

The fourth chapter presents concepts related to renewable energy systems and some concepts related to problems and challenges to the system, in addition to the results of the simulation of a system after the integration of renewable energy systems using the ETAP program.

Chapter 1: Power system studies

1.1 Power System:

Now in developed and developing nations, the availability of electrical power is necessary for economic growth. The many important items cannot be produced without energy. Without electricity, which is a necessary component of modern life, individuals find it challenging to do their tasks.

The generating system, transmission system, and distribution system are the three main parts of the electrical power system. The distribution system delivers electricity to the end user through substations that are connected to the generating units by a high voltage (HV) transmission system. Any breaks in these connecting cables have the potential to stop the system's power supply [1].

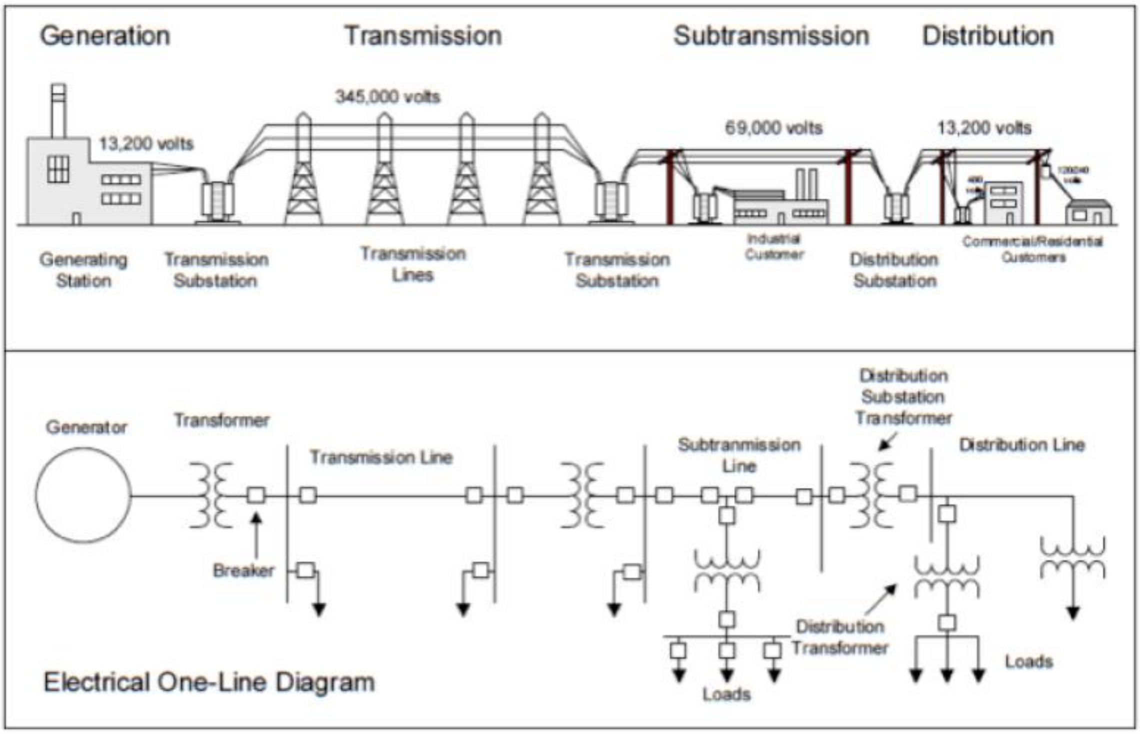


Figure 1 Typical electric power system single-line diagram[2]

1.2 The structure of the power system:

An interconnected power system is a complex enterprise that may be subdivided into the following major subsystems:

- Generation Subsystem
- Transmission and Sub transmission Subsystem
- Distribution Subsystem
- Utilization Subsystem

1.2.1 Generation Subsystem:

This includes generators and transformers.

Generators: The three-phase ac generator, an alternator or synchronous generator, is a fundamental and essential part of power systems.

Two synchronous rotating fields are included in generators. One field is created by a rotor that is rotated at synchronous speed and activated by dc current. The three-phase armature currents in the stator windings create the other field. Excitation systems provide the rotor windings with dc current. Older machines have dc generators located on the same shaft as the exciters, which excite slip rings. Asynchronous excitation systems, which are now used in systems, utilize ac generators with revolving rectifiers. Generator voltage is maintained and reactive power flow is managed by the excitation system. Ac generators are able to produce high power at high voltage, often 30 kV, since they do not use a commutator [3].

The source of the mechanical power, also known as the prime mover, may be internal combustion engines, gas turbines, steam turbines powered by the combustion of coal, gas, and nuclear fuel, or even hydraulic turbines.

1.2.1.1 Transformers: From one voltage level to another, the transformer efficiently transmits electricity. With the exception of losses in the secondary, the power transferred from the primary is extremely similar. transformer Power transmission across long distances is made possible by the use of a step-up transformer, which reduces line losses [3].

"The generation subsystem may be called GENCO"[4], responsible for generating electric power as per the predicted load requirements

1.2.2 Transmission and Sub transmission Subsystem:

Electricity from producing units is transferred via an overhead transmission network to the distribution network, which in turn feeds the load. Transmission lines also link nearby utilities, allowing the dispatch of electricity within regions under natural conditions and the transfer of electricity across areas in times of emergency [3].

The transmission subsystem may be called" TRANSCO" [4].

Figure 2 Traditional Transmission line.[1]

1.2.3 Distribution Subsystem:

The distribution system links the equipment at the consumers' service entrances to the distribution substations. The load is supplied by the primary distribution lines, which have a voltage range of 4 to 34.5 kV and cover a certain geographic region [3].

The distribution subsystem may be called "DISCOM"[4]

1.3 Power flow studies:

Power flow studies are conducted to calculate voltages, active and reactive power, etc. at various locations in the network for different operating possibilities. These calculations are based on restrictions on generator capacities, specified net interchange across operating systems, and a number of other factors. Power flow or load flow solutions are essential for a continuous evaluation of the performance of the power systems and for adopting suitable control measures when necessary. In practice, various power flow solutions will need to be used under different conditions [5].

1.3.1 Necessity for power flow studies

The necessity for power flow studies

There are several reasons why power flow studies are carried out, some of which include the following:

1.The line flows.

2. The system voltage profile and bus voltages

3. How does adding additional circuits and changing the setup affect system loads

4. The impact on system loads and corresponding effects of a temporary loss of transmission capacity and (or) generation.

5. System loading and in-phase and quadrative boost voltages

6. How the economy is run

7. Minimization of system loss

8. Setting the transformer tap for economical operation

9. Changing conductor sizes and system voltages may be able to improve an existing system[5].

1.3.2 Bus classification:

There is a bus connecting each node to a generator. In power, each bus has 4 quantities of is voltage magnitude, voltage angle, active power, and reactive power. In the system, two quantities are given and two quantities are determined. Depending on the calculation of the quantities the buses are classified into three types. The loads used in load flow studies are constant and defined for both real and reactive power consumption. Determining the voltage angle and voltage magnitude of each bus when the power is generated is the primary goal of a load analysis. For that classify different busses shown in the following figure[6]:

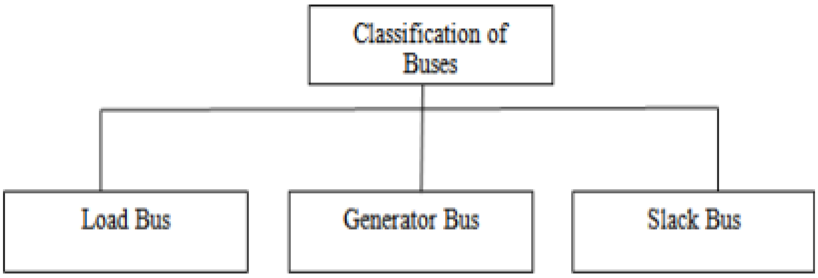


Figure 3 Classification of buses

1.3.2.1 Load Buses: Load buses are connected to the load side of the system. Which is known quantities are active power(P) and reactive power (Q). And the determined quantities are voltage magnitude(|V|) and the voltage angle(δ). In the system 20% of load buses are present.

1.3.2.2 Voltage Controlled Buses: The generator bus is connected to the generator of the system. The system's active power (V) and voltage magnitude (|V|) are known quantities. Reactive power (Q) and voltage angle (δ)are further unknowns. The primary mover of the bus controls the generator, and the voltage is controlled by the voltage. 70% of the system's generator buses are present[7].

1.3.2.3 Slack or Swing Bus: Because it serves as a reference for all other buses, the bus known as No. 1 is also known as the reference bus. All other buses are measured against it as the reference. This bus has a 0° degree angle. Voltage magnitude (|V|) and voltage angle (δ)are the bus's two well-known parameters. There is a 10% slack bus in the system.

1.3.2.4 Bus Admittance Matrix:

1. The first step is to number all the nodes of the system from 0 to n. Node 0 is the reference node (or ground node).
2. Replace all generators by equivalent current sources in parallel with an admittance.
3. Replace all lines, transformers, loads to equivalent admittances whenever possible.

4. The bus admittance matrix Y is then formed by inspection as follows (this is similar to what we learned in circuit theory): sum of admittances connected to node iiy = i and yij = y ji = -sum of admittances connected from node i to node
5. The current vector is next found from the sources connected to nodes 0 to n. If no source is connected, the injected current would be 0.
6. The current vector is next found from the sources connected to nodes 0 to n. If no source is connected, the injected current would be 0.

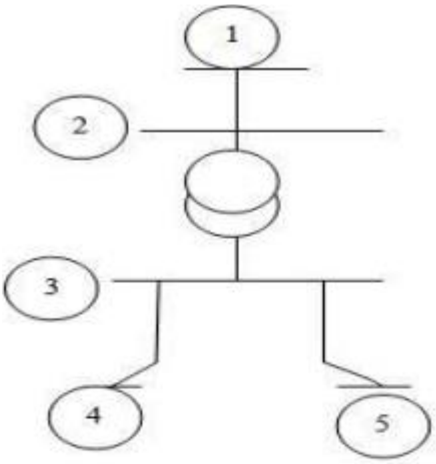


Figure 4 one line diagram of 6 bus system

1.3.3 The power flow methods:

1.3.3.1 Gauss-Siedel (GS) load flow method:

With the slack bus voltage assumed (usually V1 = 1 $\angle 0^0$ p.u.), the remaining (n-1) bus voltages are found through iterative process as follows

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos\left(\theta_{ij} - \delta_i + \delta_j\right) \quad \textbf{(1.1)}$$

$$Q_{i=-} \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin\left(\theta_{ij} - \delta_i + \delta_j\right) \quad \textbf{(1.2)}$$

The equation 1 and 2 are called static load flow equations.

$$I_i = \frac{P_i - jQ_i}{V_i^*} \quad \textbf{(1.3)}$$

$$V_i = \frac{1}{Y_{ii}}\left(I_i - \sum_{\substack{j=1 \\ j\neq 1}}^{n} Y_{ij}V_j\right) i = 2,3,4 \dots n \quad \textbf{(1.4)}$$

For (k+1) th iteration, the voltage equation becomes

$$V_i^{(k+1)} = \frac{1}{Y_{il}}\left[\frac{P_i - jQ_i}{\left(V_i^k\right)^*} - \sum_{j=1}^{i-1}\left(Y_{ij}V_j^{k+1}\right) - \sum_{j=i+1}^{n}\left(Y_{ij}V_j^k\right)\right] \quad \textbf{(1.5)}$$

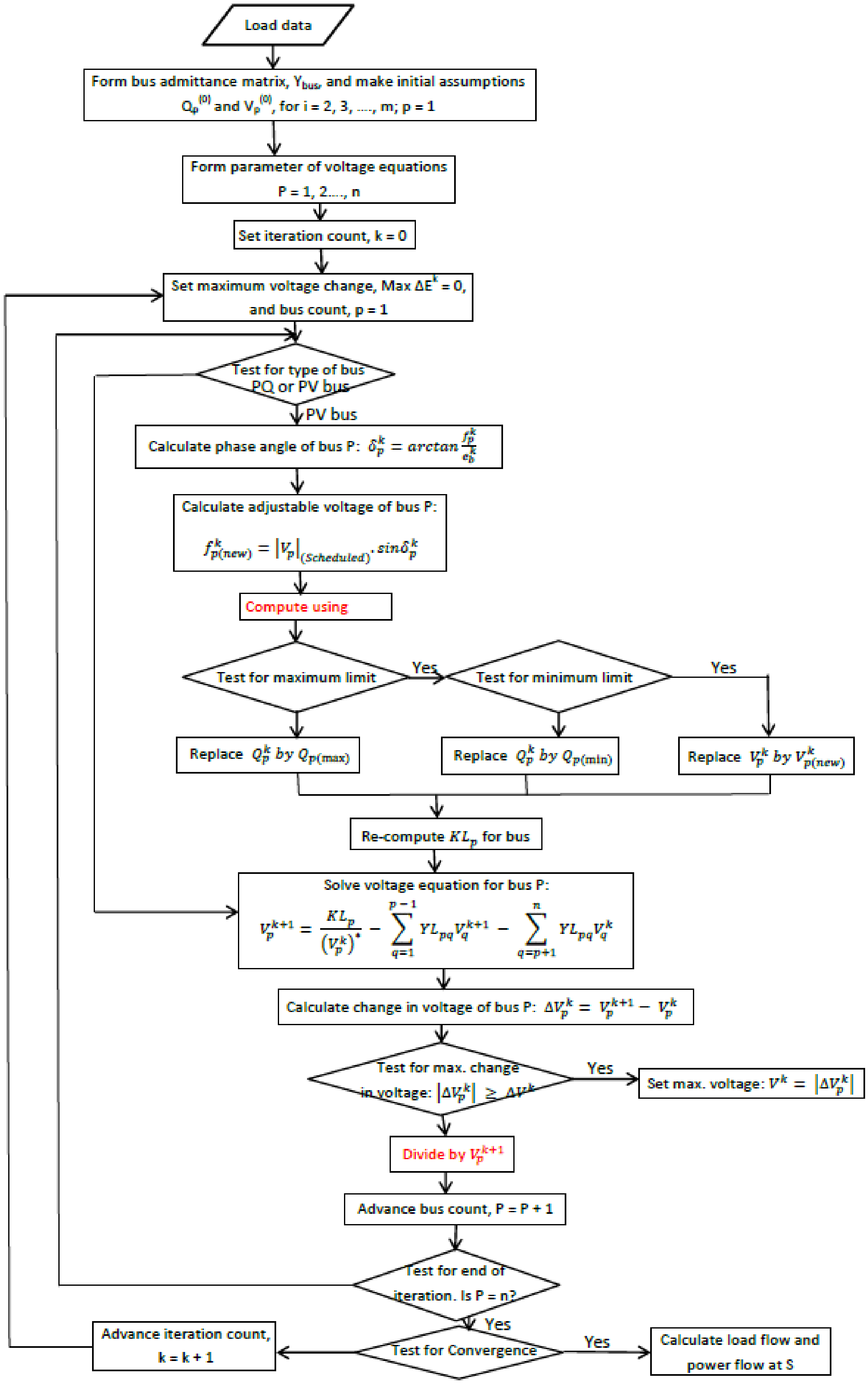


Figure 5 Flow Chart for Load-Flow Solution: Gauss-Seidel Iteration[8]

1.3.3.2 Newton-Raphson (NR) load flow method:

Because of the quadratic convergence, the Newton-Raphson method is mathematically superior to the Gauss-Siedel method[9]. It is found to be a more efficient method for large power systems. The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\delta$ and voltage magnitude ΔV with the small changes in active and reactive power ΔP and ΔQ.

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = [\mathrm{J}]\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix}$$

$$\text{here } [\mathrm{J}] = \begin{bmatrix}\mathrm{J1} & \mathrm{J2}\\ \mathrm{J3} & \mathrm{J4}\end{bmatrix}$$

The matrix of partial differentials is called the Jacobian matrix [J]. The elements of the Jacobian are calculated by differentiating the active power and reactive power Eqs.1 & 2 and substituting the estimated values of voltage magnitude and phase angle.

Element of J matrix	Order of **J** matrix elements	Diagonal elements	Off-diagonal elements
J1	$(\mathrm{n} - 1) \times (\mathrm{n} - 1)$	$\frac{\partial P_i}{\partial\vert\delta_i\vert} = \Sigma_{jzi}\vert V_i\vert V_j \Vert Y_{ij} \vert \sin\left(\theta_{ij} - \delta_i + \delta_j\right)$	$\frac{\partial P_i}{\partial\vert\delta_j\vert} = -\vert V_i\vert\vert V_j\vert\vert Y_v\vert\sin\left(\theta_{ij} - \delta_i + \delta_j\right)\cdot j \neq k$
J2	$(\mathrm{n} - 1)\mathrm{x}(\mathrm{n} - 1 - \mathrm{n}_w)$	$\frac{\partial P_i}{\partial\vert V_i\vert} = 2\vert Vi\vert\vert Y_{ii}\vert\cos\ \theta_{1i} + \Sigma_{j+1}\vert V_i\vert Y_{it}\ \vert\cos\left(\theta_{1y} - \delta_i + \delta_j\right)$	$\frac{\partial P_i}{\partial\vert V_j\vert} = \vert V_i\vert\vert Y_{tj}\vert\cos\left(\theta_{ij} - \delta_i + \delta_j\right)\cdot j \neq i$
J3	$\left(\mathrm{n}\cdot 1 - \mathrm{n}_p\right) \times (\mathrm{n} - 1)$	$\frac{\partial Q_i}{\partial\vert\delta_i\vert} = \Sigma_{j\neq 1}\vert V_i\vert\vert V_j \Vert Y_{ij}\vert\cos\left(\theta_{ij} - \delta_1 + \delta_j\right)$	$\frac{\partial Q_i}{\partial\vert\delta_j\vert} = -\vert V_i\vert\vert V_j\vert\vert Y_j\vert\cos\left(\theta_j - \delta_i + \delta_j\right)$
J4	$(\mathbf{n} - 1 - \mathbf{n}_w) \times \left(\mathrm{n} - 1 - \mathbf{n}_{pw}\right)$	$\frac{\partial Q_i}{\partial\vert V_i\vert} = -2\vert Vi \Vert V_{ii}\vert\sin\ \theta_{i!} - \sum_{ik}\vert V_i\vert\vert Y_{ju}\vert\sin\left(\theta_{ij} - \delta_i + \delta_i\right)$	$\frac{\partial Q_i}{\partial\vert V_j\vert} - \vert V_i\vert\vert Y_{ij}\vert\sin\left(\theta_{ij} - \delta_i + \delta_j\right)j \neq i$

Table 1 Description of Jacobian matrix

Where n_{pv} is the number of PV buses.

The terms $\Delta P_i^{\ r}$ and ΔQ_i^r are the difference between the scheduled and calculated valued, known as mismatch vector or power residuals, given by

P_i (scheduled) – P_i^r calculated = ΔP_i^r

Qi (scheduled) – Q_i^r calculated = ΔQ_i^r

Qi (scheduled) – Q_i^r calculated = ΔQ_i^r (1) to update voltage magnitude and angles:

$|V|^{(r+1)} = |V|^r + |\Delta V|^r$

$\delta(r+1) = \delta\ r + \Delta\delta\ r$

where r = no. of iteration.

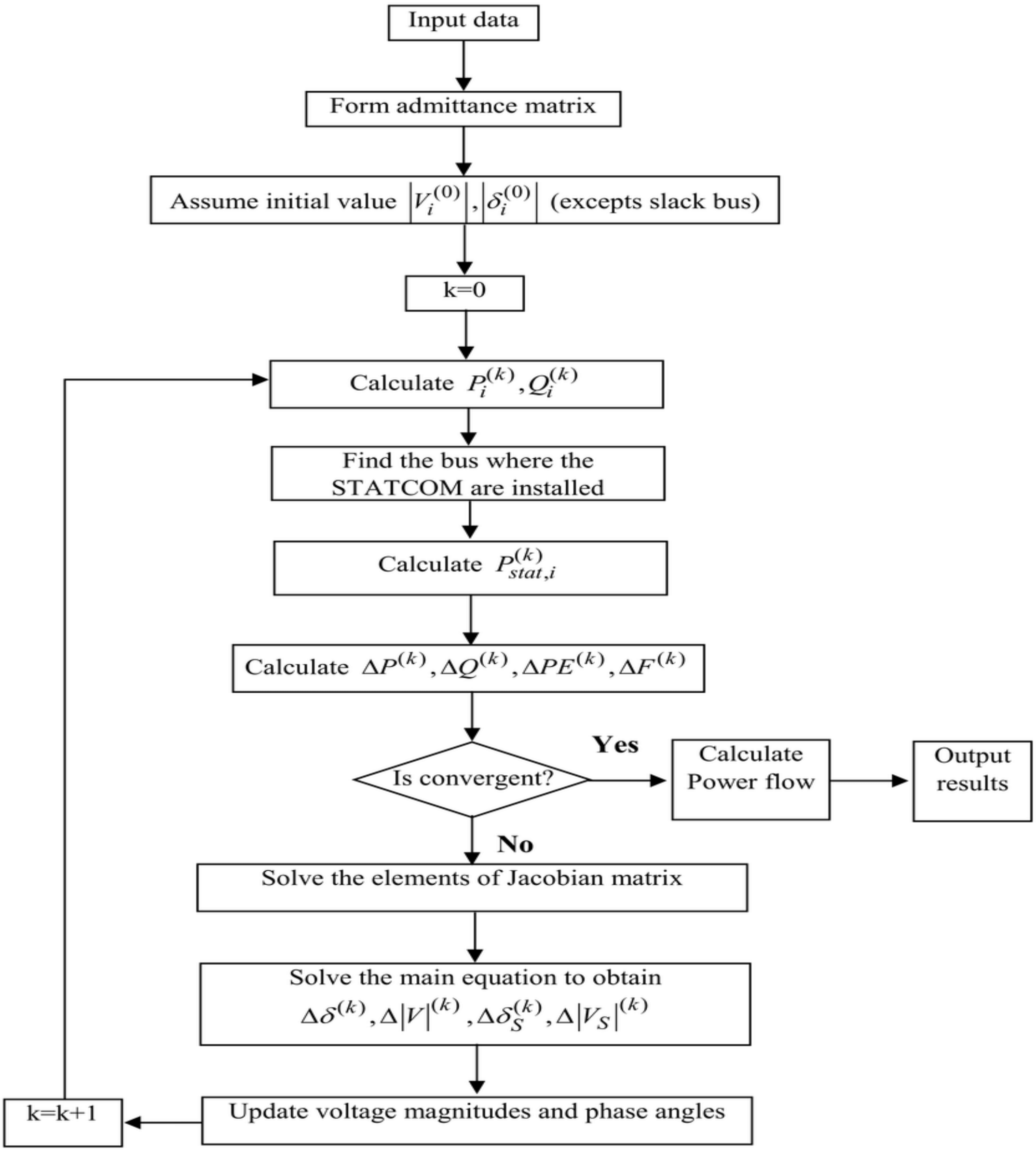


Figure 6 Flowchart of the Newton-Raphson method[10]

1.4 Faults in electrical power systems:

The fault in the power system is defined as the defect in the power system due to which the current is distracted from the intended path. The fault creates the abnormal condition which reduces the insulation strength between the conductors. The reduction in insulation causes excessive damage to the system.

Figure 7 Electrical Faults [11]

1.4.1 Types of faults in power system:

The fault in the power system is mainly categorized into two types they are

- **Open Circuit Fault**
- **Short Circuit Fault**

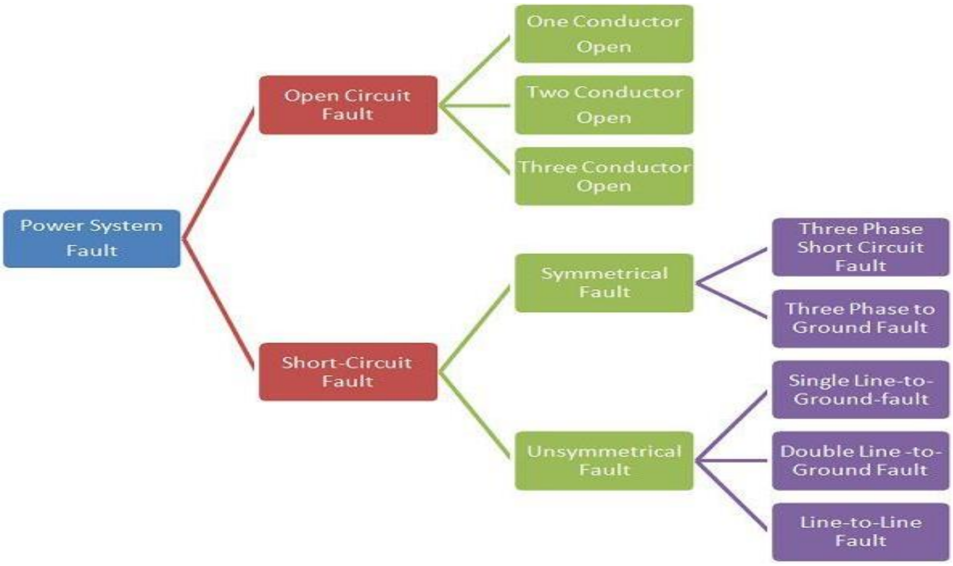


Figure 8 The different types of power system fault[12]

Many physical factors, like lightning, strong winds, earthquakes, etc., can cause faults in the electricity system. It could also happen as a result of accidents like falling from a tree, hitting a support structure with a car, an airplane crashing, etc[12].

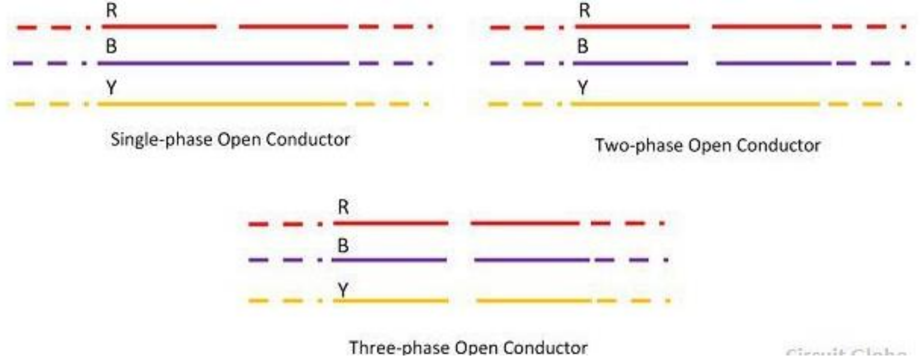
- **Open Circuit Fault:**

One or two conductors failing is the primary source of the open circuit failure. The name series fault also knows as the open circuit fault because it happens in series with the line. These faults have an impact on the system's reliability [12].

Asymmetrical or unbalanced faults are two other forms of faults in addition to three-phase open circuits. So, keep in mind that the transmission line is operating under the initial balanced load of the open-circuit fault. The alternator's load reduces if one of the three phases' spreads, and because of the low load, the alternator's speed rises, causing it to move a bit faster than synchronous speed. This over-alternator speed results in overvoltage in the transmission line [11].

The open circuit fault is categorized as:

- Open Conductor Fault
- Two conductors Open Fault
- Three conductors Open Fault.



Single-phase Open Conductor

Two-phase Open Conductor

Three-phase Open Conductor

Figure 9 The open circuit fault

- **Short-Circuit Fault:**

A short circuit can be defined as an abnormal connection of very low impedance between two points of different potential, whether made intentionally or accidentally.

These faults are the most common and dangerous ones, causing abnormally high currents to flow through the device or transmission lines. The equipment suffers extensive damage if these faults are allowed to continue, even for a small period. Shunt faults are another name for short circuit faults. These problems are caused on by a failure in the insulation between the phase conductors, the ground, or both.[11]–[13]

The short-circuit fault is divided into the

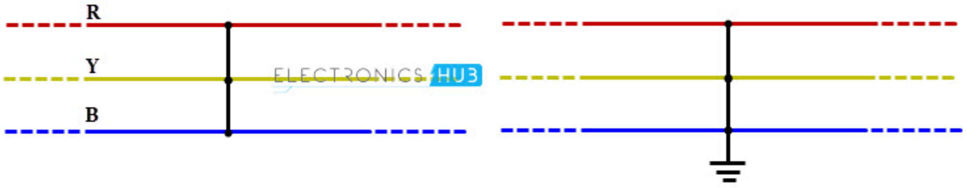
- **Symmetrical**

line-line-line
line-line-line-ground

- **Unsymmetrical fault.**

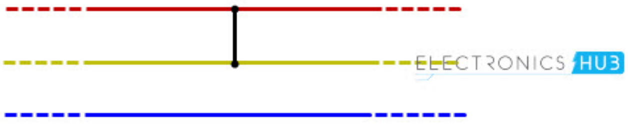
Line-ground
Line-line
Line-line-ground

Short-circuit Faults



(a). Three-phase clear of earth

(b). Three-phase-to-earth



(c). Phase-to-phase

Figure 10 Short-Circuit Faults

1.5 Power-system architecture:

A power system's many parts can be configured in a variety of ways. The cost of the investment and the amount of electrical energy available depend on the complexity of the eventual design. So, choosing an architecture for a particular application depends on finding the right balance between technical requirements and cost [14].

Architectures include the following:

1.5.1.1 Radial systems:

- Single-feeder
- Double-feeder
- Parallel-feeder
- Dual supply with double busbars.

1.5.1.2 Loop systems:

- Open loop,
- Closed loop.

1.5.2 Systems with internal power generation:

- Normal source generation,
- Replacement source generation.

Architecture	**Use**	**Advantages**	**Drawbacks**
Radial			
Single-feeder radial	Processes not requiring continuous supply E.g., a cement works	Most simple architecture Easy to protect Minimum cost	Low availability Downtime due to faults may be long A single fault interrupts supply to the entire feeder
Double-feeder radial	Continuous processes: steel, petrochemicals	Good continuity of supply Maintenance possible on busbars of main switchboard	Expensive solution Partial operation of busbars during maintenance
Double busbars	Processes requiring high continuity of service Processes with major load changes	Good continuity of supply Flexible operation: no-break transfers Flexible maintenance	Expensive solution Requires automatic control functions
Loop systems			
Open loop	Very large power systems Major future expansion Loads concentrated in different zones of a site	Less expensive than closed loop Simple protection	Faulty segment can be isolated during loop reconfiguration Requires automatic control functions
Closed loop	Power system offering high continuity of service Very large power systems Loads concentrated in different zones of a site	Good continuity of supply Does not require automatic control functions	Expensive solution Complex protection system
Internal power generation			
Normal source generation	Industrial process sites producing their own energy E.g., paper plants, steel	Good continuity of supply Cost of energy (energy recovered from process	Expensive solution
Replacement source (source changeover)	Industrial and commercial sites E.g., hospitals	Good continuity of supply for priority outgoing feeders	Requires automatic control functions

Table 2 the main characteristics of each architecture for comparison.[14]

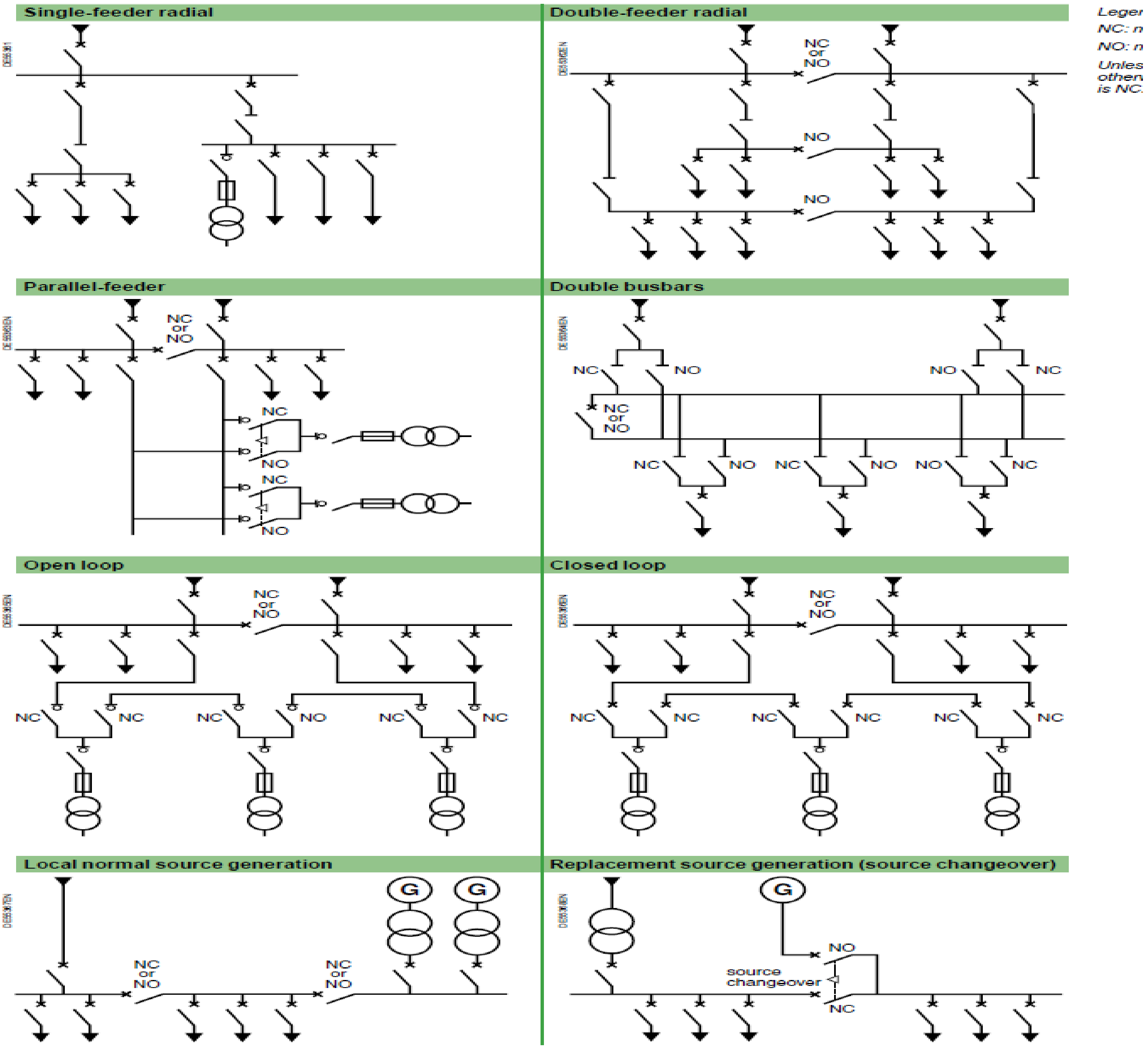


Figure 11 Examples of architectures[14]

1.6 Transmission line parameters:

One of the key parts of an electric power system is the power transmission line. Its major task is to move electric energy efficiently between distribution substations that are typically far off from the power sources [15].

A transmission line's design is influenced by four electrical parameters:

- Series resistance
- Series inductance
- Shunt capacitance
- Shunt conductance

Quantity	Symbol	Unit
Resistance	R	Ohm (Ω)
Inductance	L	Henry (H)
Capacitance	C	Farad (F)
Conductance	G	Siemens (S or Ω^{-1})

Table 3 Symbols and Units for Transmission Line Parameters

1.6.1 Series resistance:

The resistance of the conductor is the most important cause of power loss in a power line. Direct-current resistance is given by the familiar formula:

$$R_{\mathrm{dc}} = \frac{\rho l}{A} \text{ohms} \tag{1.6}$$

where

ρ is the conductor resistivity at a given temperature (Ω m)

ʟ is the conductor length (m)

A is the conductor cross-section area (m^2)

1.6.2 Series inductance:

The inductance of a magnetic circuit that has a constant permeability m can be obtained by determining the following:

- Magnetic field intensity H, from Ampere's law
- Magnetic flux density B (B=µH)
- Flux linkages λ
- Inductance from flux linkages per ampere (L=λ/I)

1.6.3 Shunt capacitance:

Gauss' law is used to determine the electric field strength between the conductors that compose the transmission line in order to calculate capacitance. The conductor bundling and spacing both have an impact on the electric field strength. The impact of the earth is taken into account in various capacitance calculations.

$$\text{Density }_p = \frac{q}{A} = \frac{q}{2\pi x}\ \text{(C)}$$

$$E_P = \frac{\text{Density}_P}{\varepsilon} = \frac{q}{2\pi\varepsilon_0 x}\ (\text{V/m}) \qquad \textbf{(1.7)}$$

Where

Density P is the electric flux density at point P (C)

E_P is the electric field intensity at point P (V/m)

A is the surface of a concentric cylinder with 1m length and radius x (m^2)

$\varepsilon = \varepsilon 0 = 10^{-9}/36\pi$ is the permittivity of free space assumed for the conductor (F/m)

The potential difference or voltage difference between two outside points P_1 and P_2 with corresponding distances x_1 and x_2 from the conductor center.

$$C_{P1-P2} = \frac{q}{V_{P1-p2}} = \frac{2\pi\varepsilon_0}{\ln[x_2/x_1]}\ (\text{F/m}) \qquad (1.8)$$

1.6.4 Shunt conductance:

Shunt conductance is a shunt parameter of transmission line parameters. It is the flow of leakage current between conductors or between a conductor and earth at the insulators of the transmission line. This flow of leakage current depends upon the condition of the air between transmission lines. Generally, the value of shunt conductance on account of leakage current is very small and can be neglected.

1.7 Conclusion:

This chapter introduces the basic concepts of power systems, such as the basic structure of power distribution stations, the basic concepts of energy flow, as well as the types of faults that occur in the system in addition to the parameter of transmission lines.

Chapter 2: Transient Stability Studies

2.1 Introduction:

Because of the increasing population, the number of commercial buildings, and the industrial sector, there is a great need for electrical power. As a result of this high demand, networks are becoming bigger and more linked. Maximum power transfer from generating stations to consumer terminals throughout large linked networks is becoming more important to power utility companies. Because of various types of disturbances, it is sometimes hard to transfer the optimum amount of power when there are several synchronous machines in play, along with huge, interconnected networks. Small disturbances (perturbations) and large disturbances are the two groups into which these disturbances fall. (perturbation). Small perturbations, such as continually occurring random variations in the system's load, are one type of disturbance. A power system could face large perturbations such as line faults, the loss of large generating units, the loss of important transmission facilities, and the loss of large loads. The stability of the power system is compromised by any disturbances.[16]

2.2 Stability of power system:

Stability is the ability of a dynamic system to remain in the same operating state even after a disturbance that occurs in the system. When used in a power system, stability is defined as the ability of the system or component of the system to develop restoring forces between its parts that are equal to or greater than the disturbing force, restoring a state of equilibrium between the elements [5].When a co-generation plant, is used in reference to any facility containing large synchronous machinery) is connected to the transmission grid, it changes the system configuration as well as the power flow pattern. This may result in stability problems both in the plant and the supplying utility. **Figure 12** and **Figure 13** are the time-domain simulation results of a system before and after the connection of a co-generation plant. The increased magnitude and decreased damping of machine rotor oscillations shown in these figures indicate that the system's dynamic stability performance has deteriorated after the connection. This requires joint studies between utility and co-gen systems to identify the source of the problem and develop possible mitigation measures.

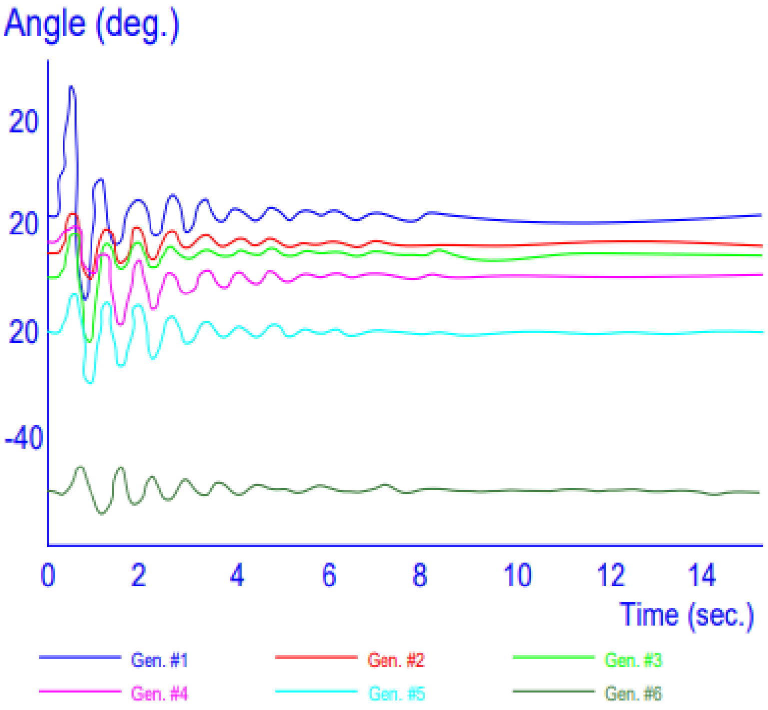


Figure 12 System response – No co-gen plant[17]

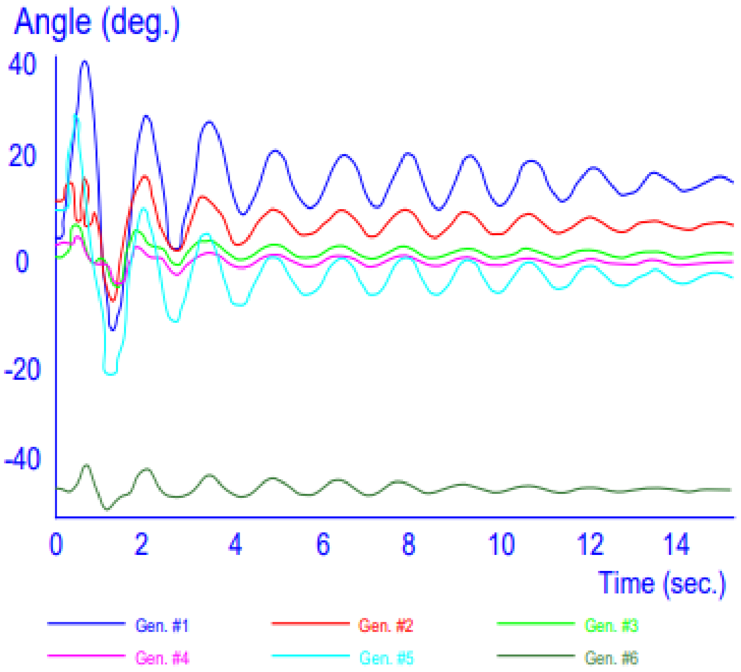
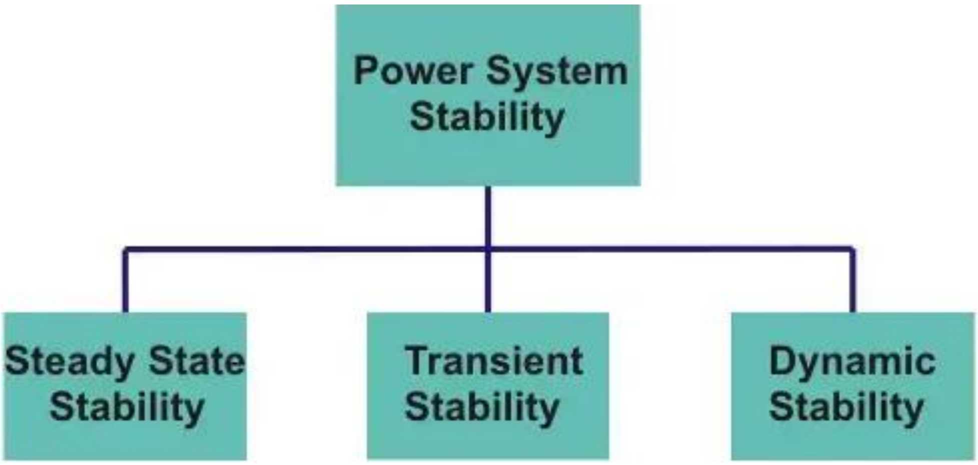


Figure 13 Low-frequency oscillation after the connection of the co-gen plant[17]

2.3 Classification of Power System Stability:

There are three modes of behaviour generally identified for the power system under dynamic condition.



2.3.1 Steady state stability:

Steady-state stability relates to the response of synchronous machine to a gradually increasing load. It is basically concerned with the determination of the upper limit of machine loading without losing synchronism, provided the loading is increased gradually.

In steady-state stability, the synchronous generator regains synchronism after a small disturbance, as shown in Figure14

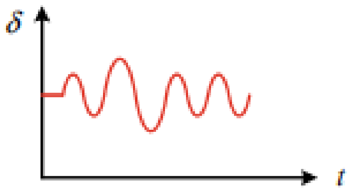


Figure 14 Steady-state stability curve

Illustration of Steady State Stability concept:

If the internal voltages of the two machines are E_G and E_M and the phase angle between them is θ, it can easily be demonstrated that the real power transmitted from the generator to the motor is:

$$P = \frac{E_G E_M}{X} \sin\theta \qquad (2.1)$$

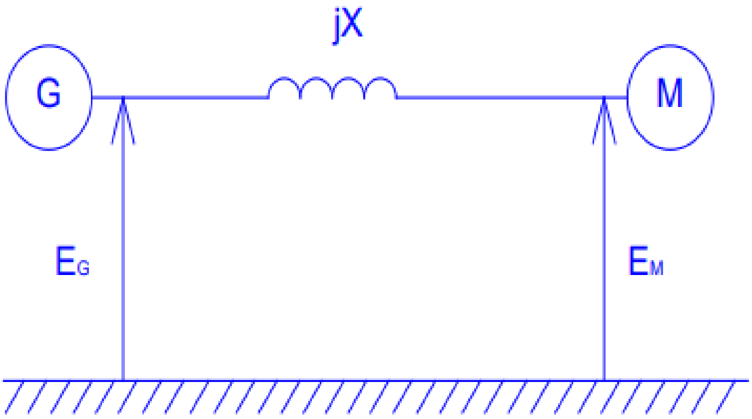


Figure 15 Simplified two-machine power system

The maximum value of P obviously occurs when θ = 90°. Thus:

$$P_{max} = \frac{E_G E_M}{X} \tag{2.2}$$

This is the simplified two-machine system's steady-state stability limit. Any effort to distribute extra power than Pmax will cause the two machines to fall out of step (lose synchronism) for specific internal voltage levels.

This short example shows how at least three electrical characteristics of a power system affect stability. They are as follows:

- Internal voltage of the generator(s)
- Reactance(s) of the machines and transmission system
- Internal voltage of the motor(s) if any

2.3.2 Dynamic stability:

Dynamic stability refers to a system's ability to withstand small disturbances that create oscillations without magnifying them. A system is said to be dynamically stable if such oscillations do not reach a particular amplitude and disappear quickly. However, if these oscillations continue to amplify, the system is considered dynamically unstable. The connection of control systems is typically the cause of this type of instability.

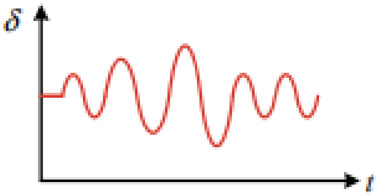


Figure 16 Dynamic stability curve

2.3.3 Transient stability:

It includes major disturbances like generator failure, line switching, faults, and sudden load changes. Stability is a fast phenomenon that generally appears itself within a few seconds. The objective of transient stability studies is to determine whether or not the system remains synchronized in the face of such disturbances.[18]

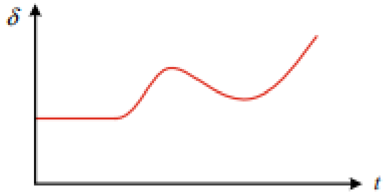


Figure 17 Transient stability curve

Power system stability mainly concerned with rotor stability analysis. For these various assumptions needed such as:

- For stability analysis balanced three phase system and balanced disturbances are considered.
- Deviations of machine frequencies from synchronous frequency are small.
- During short circuit in generator, dc offset and high frequency current are present. But for analysis of stability, these are neglected.
- Network and impedance loads are at steady state. Hence voltages, currents and powers can be computed from power flow equation.

2.4 Dynamics of a Synchronous Machine:

A synchronous machine or alternator delivers instantaneous power ($p = P + p_i$)

The expression of power with a sinusoidal current can be expressed as,

$$p = i_2 R = RI^2 \sin^2 \omega t = I^2 R(1 - \cos 2\omega t) = P + p_i \tag{2.3}$$

Here, the expression of active power due to fundamental voltage and current is,

$$P = I^2 R = \frac{V^2}{R} \tag{2.4}$$

The intrinsic power (pi) is expressed as,

$$p_i = -P\cos 2\omega t \tag{2.5}$$

In steady-state, this intrinsic power cannot be supplied by the prime mover. Generally, it is supported by the kinetic energy ($KE = J\omega^2/2$) stored in the rotating masses. Here, J is the total momentum (alternator rotor plus prime mover) of inertia and its unit is kg m^2. The kinetic energy of a synchronous machine in Mega-Joules can be written as,

$$K \cdot E = \frac{1}{2} J\omega_{sm}^2 \times 10^{-6} \text{MJ} \tag{2.6}$$

Where

- J = rotor moment of inertia in Kg-m^2
- ω sm = synchronous speed in rad (mech)/s

But

$$\omega_s = \left(\frac{P}{2}\right)\omega_{sm} = \text{rotor speed in rad (elect)/s}$$

Where

- P = number of machine poles

$$\begin{aligned} \text{KE} &= \frac{1}{2}\left(J\left(\frac{2}{P}\right)^2 \omega_s \times 10^{-6}\right)\omega_s \\ &= \frac{1}{2}M\omega_s \end{aligned}$$

Where

- $M = J(2/P)^2\omega_s \times 10^{-6}$
- = moment of inertia in MJ-s/elect rad

We shall define the inertia constant H such that:

$$G\text{H} = \text{KE} = \frac{1}{2}M\omega_s\text{MJ} \tag{2.7}$$

Where

- G = machine rating (base) in MVA (3-phase)
- H = inertia constant in MJ/MVA or MW-s/MVA

It immediately follows that

$$\begin{aligned} \text{M} &= \frac{2G\text{H}}{\omega_s} = \frac{GH}{\pi f}\text{MJ} - \text{s/ elect rad} \\ &= \frac{G\text{H}}{180f}\text{MJ} - \text{s/ elect degree} \end{aligned} \tag{2.8}$$

M is also called the inertia constant.
Taking G as base, the inertia constant in pu is

$$\begin{aligned} \text{M(pu)} &= \frac{\text{H}}{\pi f}\text{s}^2/\text{ elect rad} \\ &= \frac{\text{H}}{180\text{f}}\text{s}^2/\text{ elect degree} \end{aligned} \tag{2.9}$$

2.5 Single Machine with infinite bus:

An infinite bus is an ideal voltage source is one that maintains constant voltage values for magnitude, frequency, and phase angle. Here, δ represents the machine's angle with respect to the infinite bus. The torque or load angle refers to this angle. The angular deviation in electrical degrees from the synchronously rotating reference axis is known as the torque angle or load angle. Through transmission lines, the generator supplies the endless bus with active power[16] The synchronous machine is represented by a voltage source $(E\lfloor\delta)$ behind the direct axis reactance.

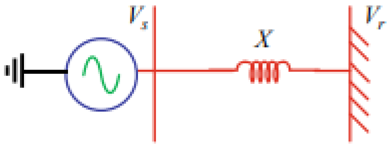


Figure 18 Synchronous machine with an infinite bus

The voltage at the generator terminal can be written as,

$$V_s = E \mid \delta \tag{2.10}$$

The voltage at the infinite bus is,

$$V_r = V\lfloor 0^\circ \tag{2.11}$$

The current in the circuit in Figure 8 can be written as,

$$I_s = \frac{V_s - V_r}{jX_d' + jX_{\mathrm{TL}}} = \frac{V_s - V_r}{jX} \tag{2.12}$$

Substituting Eqs. **(2.10)** and **(2.11)** into Eq. **(2.12)** yields,

$$I_s = \frac{E\underline{\delta} - V\lfloor 0^\circ}{jX} \tag{2.13}$$

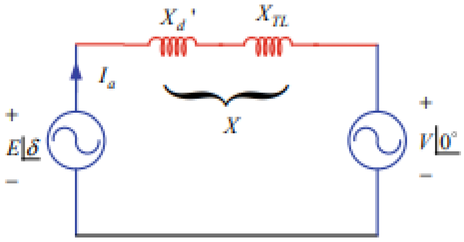


Figure 19 Equivalent circuit of a machine to an infinite bus

The conjugate value of the current is,

$$I_s^* = \frac{E\lfloor -\delta - V\lfloor 0^\circ}{X\lfloor -90^\circ} \tag{2.14}$$

The single-phase sending end real power and reactive power can be derived as,

$$S = P_s + jQ_s = V_s I_s^* \qquad \textbf{(2.15)}$$

Substituting Eqs. **(2.10)** and **(2.15)** into Eq. **(2.15)** yields,

$$S = P_s + jQ_s = E\underline{\delta}\,\frac{E\underline{-\delta}-V\lfloor 0^\circ}{X\lfloor -90^\circ} \qquad \textbf{(2.16)}$$

$$P_s + jQ_s = \frac{E^2}{X}\Big\lfloor 90^\circ - \frac{EV}{X}\underline{90^\circ + \delta} \qquad \textbf{(2.17)}$$

$$P_s + jQ_s = \frac{E^2}{X}(\cos\ 90^\circ + j\sin\ 90^\circ) - \frac{EV}{X}\big(\cos\,(90^\circ + \delta) + j\sin\,(90^\circ + \delta)\big) \qquad \textbf{(2.18)}$$

$$P_s + jQ_s = j\frac{E^2}{X} + \frac{EV}{X}\sin\ \delta - j\frac{EV}{X}\cos\ \delta \qquad \textbf{(2.19)}$$

Equating the real and imaginary parts of Eq. **(2.19)** yields,

$$P_s = \frac{EV}{X}\sin\ \delta \qquad \textbf{(2.20)}$$

$$Q_s = \frac{E^2}{X} - \frac{EV}{X}\cos\ \delta \qquad \textbf{(2.21)}$$

For lossless transmission lines, the sending power is equal to the receiving end power. In case of three-phase system, this power can be written as,

$$P_e = P_s = P_r = 3\frac{EV}{X}\sin\ \delta \qquad \textbf{(2.22)}$$

At $\delta = 90^\circ, P_e = P_{max}$ Eq. **(2.22)** becomes,

$$P_{max} = 3\frac{EV}{X} \qquad \textbf{(2.23)}$$

Substituting Eq. **(2.22)** into Eq. **(2.23)** yields,

$$P_e = P_{\max}\sin\ \delta \qquad \textbf{(2.24)}$$

At $\delta = \delta_0, P_e = P_0$ Eq. **(2.24)** becomes,

$$P_0 = P_{\max}\sin\delta_0 \qquad \textbf{(2.25)}$$

$$\sin\delta_0 = \frac{P_0}{P_{\max}} \qquad \textbf{(2.26)}$$

$$\delta_0 = \text{sin-1}\ (\frac{P_0}{P_{\max}}) \qquad \textbf{(2.27)}$$

The output power of a synchronous machine depends on the torque produced by the mechanical turbine and the generator's angular speed.

In this case, the electrical power output of a synchronous machine can be written as,

$$P_e = T \times \omega_s \tag{2.28}$$

$$T = \frac{P_e}{\omega_s} \tag{2.29}$$

Substituting Eq. **(2.24)** into Eq. **(2.29)** yields,

$$T = \frac{P_{\max}}{\omega_s} \sin\delta = T_{max} \sin\delta \tag{2.30}$$

where the expression of maximum torque is,

$$T_{max} = \frac{P_{max}}{\omega_s} \tag{2.31}$$

Substituting Eq. **(2.23)** into Eq. **(2.31)** yields,

$$T_{max} = 3\frac{EV}{X\omega_s} \tag{2.32}$$

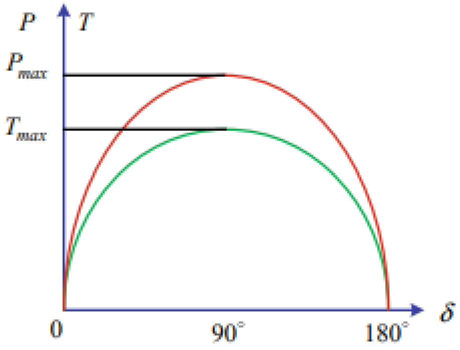


Figure 20 Variation of power and torque with a torque angle

The variations of power and torque at different torque angles are shown in Figure 20 from Eqs. **(24)** to **(30)** With a power or torque angle, it can be seen that the power and torque vary sinusoidally. Up until the torque angle reach a value of 90◦, power and torque will increase the power output will decrease and reach zero at the torque angle of 180◦ when the prime-mover input to the generator increases further. As a result, the generator accelerates as a result of excess power, increasing its speed and causing it to desynchronize. Hence, the steady-state stability limit is reached when δ =90◦.For normal steady-state operating conditions, the value of the power angle or torque angle is usually less than 90◦.[16]

2.6 Swing Equation:

The swing equation is very important to study the stability analysis of a power system. The synchronous generator's rotor rotates smoothly in steady-state conditions. However, according to the disturbance, the rotor will either accelerate or decelerate with respect to the generator's rotating air gap and start oscillation.[16][19]The equation representing this rotor oscillation is known as the swing equation. Consider a three-phase synchronous machine that is connected to a prime mover. A three-phase synchronous generator is driven by a prime mover with a torque of Tm, causing an electromagnetic torque Te according to Newton's second law states that the rotor motion may be represented as

$$J\alpha_m + T_{f\delta d} + T_e = T_m \qquad \textbf{(2.33)}$$

Equation **(2.33)** can be modified by neglecting the friction and damping torque $T_{f\&d}$as,

$$J\alpha_m = T_m - T_e = T_a \qquad \textbf{(2.34)}$$

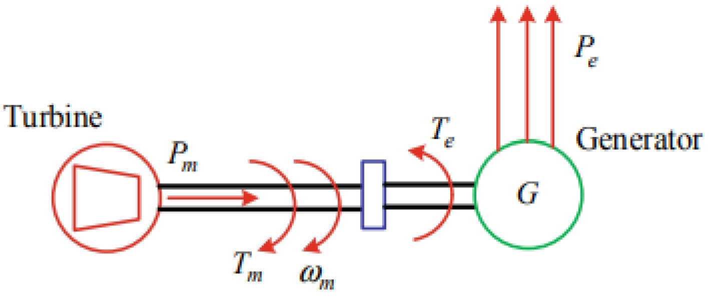


Figure 21 Generator with the turbine

Where

J is the combined moment of inertia of the generator and prime mover in kg m^2,

T_a is the accelerating torque in N m,

T_m is the mechanical torque in N m,

T_e is the electromagnetic torque in N m,

α_{m} is the rotor angular acceleration in rad/s^2.

The rotor angular acceleration is defined as the time rate of change of angular speed, and it can be expressed as,

$$\alpha_m = \frac{d\omega_m}{dt} \qquad \textbf{(2.35)}$$

However, the rotor angular velocity (ω_m) is defined as the time rate of change of angular displacement (θ_m), and it can be expressed as,

$$\omega_m = \frac{d\theta_m}{dt} \qquad \textbf{(2.36)}$$

Substituting Eq. **(2.35)** into Eq. **(2.36)** yields,

$$\alpha_m = \frac{d}{dt}\left(\frac{d\theta_m}{dt}\right) = \frac{d^2\theta_m}{dt^2} \qquad \textbf{(2.37)}$$

Substituting Eq. **(2.37)** into Eq. **(2.34)** yields,

$$J\frac{d^2\theta_m}{dt^2} = T_m - T_e = T_a \qquad \textbf{(2.38)}$$

Where the following parameters are,
θ_m is the rotor angular position with respect to fixed axis in rad,
ω_m is the rotor angular velocity in rad/s.

The main interest for stability study is the rotor speed with respect to the fixed reference axis on the stator as shown in **Figure 22** The rotor angular position with reference to the stator axis is shown in **Figure 23** and the rotor angular position with respect to a reference axis which rotates at synchronous speed is given by,

$$\theta_m = \omega_{sm}t + \delta_m \qquad \textbf{(2.39)}$$

where the following parameters are,

ω_{sm} is the synchronous angular velocity of the rotor in rad/s,

δ_m is the rotor angular position with respect to synchronously rotating reference axis in rad.

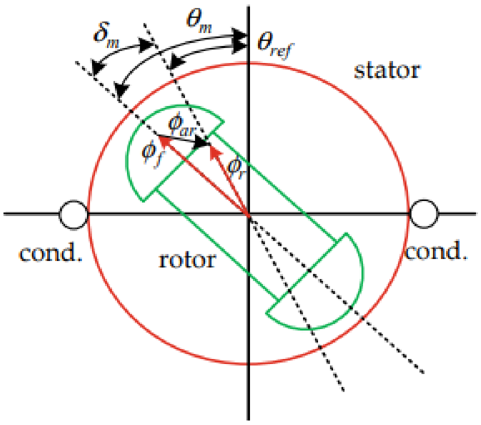


Figure 22 Rotor with the reference axis

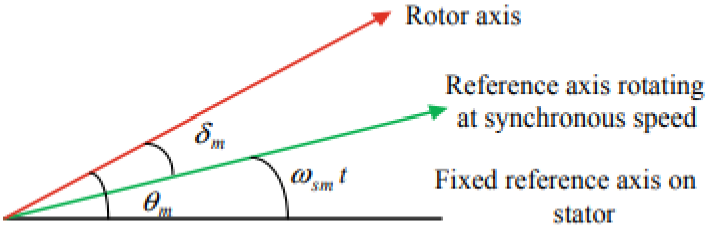


Figure 23 Rotor angular position to the reference axis

Differentiating Eq. **(2.39)** with respect to the time yields,

$$\frac{d\theta_m}{dt} = \omega_{sm} + \frac{d\delta_m}{dt} \tag{2.40}$$

Again differentiating Eq. **(2.40)** with respect to time yields,

$$\frac{d^2\theta_m}{dt^2} = \frac{d^2\delta_m}{dt^2} \tag{2.41}$$

Substituting Eq. **(2.41)** into Eq. **(2.38)** yields,

$$J\frac{d^2\delta_m}{dt^2} = T_m - T_e = T_a \tag{2.42}$$

Multiplying Eq. **(2.42)** by ω_m yields,

$$J\omega_m \frac{d^2\delta_m}{dt^2} = \omega_m T_m - \omega_m T_e \tag{2.43}$$

In general, the power is equal to torque times the angular velocity. Therefore, Eq. **(2.43)** is again modified as,

$$J\omega_m \frac{d^2\delta_m}{dt^2} = P_m - P_e \tag{2.44}$$

The angular momentum (M) is equal to the moment of inertia (J) times angular synchronous velocity ($\omega_m = \omega_s$). Therefore, Eq. **(2.44)** can be modified as,

$$M\frac{d^2\delta_m}{dt^2} = P_m - P_e \tag{2.45}$$

The angular momentum (M) is constant before the stability of a synchronous machine is disturbed or lost. In this region, the ω_m is constant, and it can be represented by ω_{sm}.

$$M = \frac{2SH}{\omega_s} = \frac{SH}{\pi f_s} \text{ MJ s/elec rad}$$

can be modified as,

$$M = \frac{2HS}{\omega_{sm}} \tag{2.46}$$

$$S = \frac{M\omega_{sm}}{2H} \tag{2.47}$$

Substituting Eq. **(2.46)** into Eq. **(2.45)** yields,

$$\frac{2HS}{\omega_{sm}} \frac{d^2\delta_m}{dt^2} = P_m - P_e \tag{2.48}$$

Equation **(2.45)** is known as swing equation. It is more convenient to express the swing equation in terms of electrical power angle rather than mechanical power angle. Let the number of poles of a synchronous generator is ρ. The relationship between the electrical power angle $\boldsymbol{\delta}$ and the mechanical power angle $\boldsymbol{\delta_m}$ is

$$\delta = \frac{P}{2}\delta_m \tag{2.49}$$

According to Eq. **(2.49),** the electrical radian frequency is expressed as,

$$\omega = \frac{P}{2}\omega_m \tag{2.50}$$

Similarly, the synchronous electrical radian frequency is expressed as,

$$\omega_s = \frac{P}{2}\omega_{\mathrm{sm}} \tag{2.51}$$

Substituting Eq. **(2.51)** into Eq. **(2.46)** yields,

$$M = \frac{2HSP}{2\omega_s} \tag{2.52}$$

$$\frac{M}{P} = \frac{HS}{\omega_s} \tag{2.53}$$

$$\frac{2M}{P} = \frac{2HS}{\omega_s} \tag{2.54}$$

Substituting Eq. **(2.53)** into Eq. **(2.48)** yields,

$$\frac{2M}{P}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{2.55}$$

Power system analysis is usually done based on the power unit values. Therefore, dividing Eq. **(2.55)** by the base power S_b yields,

$$\frac{2M}{P}\frac{1}{S_b}\frac{d^2\delta}{dt^2} = \frac{P_m}{S_b} - \frac{P_e}{S_b} \tag{2.56}$$

$$\frac{2M}{P}\frac{1}{S_b}\frac{d^2\delta}{dt^2} = P_{m(\mathrm{pu})} - P_{e(\mathrm{pu})} \tag{2.57}$$

Substituting Eq. **(2.47)** into Eq. **(2.57)** yields,

$$\frac{2M}{P}\frac{2H}{M\omega_{\mathrm{sm}}}\frac{d^2\delta}{dt^2} = P_{m(\mathrm{pu})} - P_{e(\mathrm{pu})} \tag{2.58}$$

$$\frac{2}{P}\frac{2H}{\omega_{sm}}\frac{d^2\delta}{dt^2} = P_{m(\mathrm{pu})} - P_{e(\mathrm{pu})} \tag{2.59}$$

Substituting Eq. **(2.51)** into Eq. **(2.59)** yields,

$$\frac{2}{P}\frac{2H}{1}\frac{P}{2\omega_s}\frac{d^2\delta}{dt^2} = P_{m(\mathrm{pu})} - P_{e(\mathrm{pu})} \tag{2.60}$$

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_{m(\mathrm{pu})} - P_{e(\mathrm{pu})} \tag{2.61}$$

Again, expressing ω_s in terms of frequency and the subscript pu is omitted from Eq. **(2.61)** to express the general swing equation as,

$$\frac{2H}{2\pi f_0}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{2.62}$$

$$\frac{H}{\pi f_0}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{2.63}$$

In Eq. **(2.63)**, δ represents the load angle of the generator internal emf in radians, and it dominates the amount of power that can be transferred. If the load angle expresses in electrical degrees, then Eq. **(2.63)** is further modified as,

$$\frac{H}{180 f_0}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{2.64}$$

Alternative form of Swing equation: Equation **(2.40)** can be written as,

$$\omega_m = \frac{d\theta_m}{dt} = \omega_{sm} + \frac{d\delta_m}{dt} \tag{2.65}$$

Equation **(2.33)** can be further modified by introducing damping coefficient D_{d} (Nms.) for mechanical rotational loss due to friction and windage as,

$$J\frac{d\omega_m}{dt} + D_d\omega_m = T_m - T_e \tag{2.66}$$

Substituting Eq. **(2.65)** into Eq. **(2.66)** yields,

$$J\frac{d}{dt}\left(\omega_{sm} + \frac{d\delta_m}{dt}\right) + D_d\left(\omega_{sm} + \frac{d\delta_m}{dt}\right) = T_m - T_e \tag{2.67}$$

$$J\frac{d^2\delta_m}{dt^2} + D_d\frac{d\delta_m}{dt} = T_m - T_e \tag{2.68}$$

Multiplying both sides of Eq. **(2.68)** by ω_{sm} yields,

$$J\omega_{sm}\frac{d^2\delta_m}{dt^2} + \omega_{sm}D_d\frac{d\delta_m}{dt} = \omega_{sm}(T_m - T_e) \tag{2.69}$$

$$J\omega_{sm}\frac{d^2\delta_m}{dt^2} + \omega_{sm}D_d\frac{d\delta_m}{dt} = \omega_{sm}\left(\frac{P_m}{\omega_m} - \frac{P_e}{\omega_m}\right) \tag{2.70}$$

During a small disturbance, the speed of a synchronous machine is normally close to synchronous speed so that $\omega_m = \omega_{sm}$ and Eq. **(2.70)** becomes,

$$J\omega_{sm}\frac{d^2\delta_m}{dt^2} + \omega_{sm}D_d\frac{d\delta_m}{dt} = P_m - P_e \tag{2.71}$$

Again, substituting $M_m = J\omega_{sm}$ is the angular momentum of the rotor at synchronous speed and $D_m = \omega_{sm}D_d$ is the damping coefficient in Eq. **(2.70)** as,

$$M_m\frac{d^2\delta_m}{dt^2} + D_m\frac{d\delta_m}{dt} = P_m - P_e \tag{2.72}$$

Equation **(2.72)** is the fundamental swing equation derived from the rotor dynamics.

2.7 Equal area criterion:

The sine term is part of the swing equation's accelerating power. a nonlinear differential equation will therefore be the solution to a swing equation. A nonlinear equation does not have a simple or easy solution.[16] The equal area criterion, a direct technique, is used to determine the system's stability. This method is based on a graphic representation of the stored energy in the rotating machine. It is often known as a graphical method for stability analysis. This method can only be used with a single machine into an infinite bus. For an unstable system, the torque angle (δ) increases indefinitely with time. Whereas for a stable system, torque angle (δ) undergoes oscillations, and after some time, it will die out.[19], [20]

This equation $\frac{H}{\pi f_0}\frac{d^2\delta}{dt^2} = P_m - P_e$

can be rearranged as $\frac{d^2\delta}{dt^2} = \frac{\pi f_0}{H}(P_m - P_e)$ **(2.73)**

Multiplying Eq. **(2.73)** by $2\frac{d\delta}{dt}$ dt yields,

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = \frac{2\pi f_0}{H}(P_m - P_e)\frac{d\delta}{dt} \tag{2.74}$$

$$\frac{d}{dt}\left[\left(\frac{d\delta}{dt}\right)^2\right] = \frac{2\pi f_0}{H}(P_m - P_e)\frac{d\delta}{dt} \tag{2.75}$$

$$d\left[\left(\frac{d\delta}{dt}\right)^2\right] = \frac{2\pi f_0}{H}(P_m - P_e)d\delta \qquad \textbf{(2.76)}$$

Integrating Eq. **(2.76)** from δ_0 to δ yields,

$$\left(\frac{d\delta}{dt}\right)^2 = \frac{2\pi f_0}{H}\int_{\delta_0}^{\delta}(P_m - P_e)d\delta \qquad \textbf{(2.77)}$$

$$\frac{d\delta}{dt} = \sqrt{\frac{2\pi f_0}{H}\int_{\delta_0}^{\delta}(P_m - P_e)d\delta} \qquad \textbf{(2.78)}$$

Equation **(2.78)** represents the speed of the machine with respect to the synchronously rotating reference axis. both stable and unstable machine rotor angle plots are presented. as shown in **Figure 20** the rotor angles in a condition of instability increase with time. However, in a stable condition, it oscillates and dies out due to damping. Under the stable condition, the rate of change of the rotor angle will be zero in some instants.

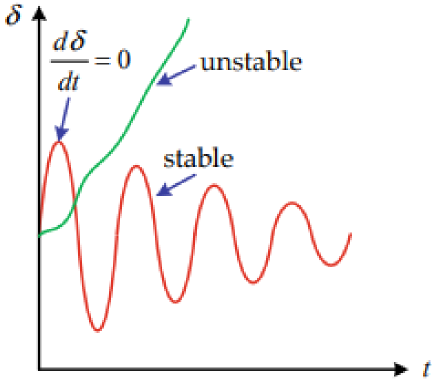


Figure 24 Variation of rotor angles with time

For stable condition of a system setting $\frac{d\delta}{dt} = 0$ and Eq. **(2.78)** becomes,

$$\frac{d\delta}{dt} = \sqrt{\frac{2\pi f_0}{H}\int_{\delta_0}^{\delta}(P_m - P_e)d\delta} = 0 \qquad \textbf{(2.79)}$$

$$\frac{2\pi f_0}{H}\int_{\delta_0}^{\delta}(P_m - P_e)d\delta = 0 \qquad \textbf{(2.80)}$$

$$\int_{\delta_0}^{\delta}(P_m - P_e)d\delta = 0 \qquad \textbf{(2.81)}$$

From Eq. **(2.81)**, it is seen that the positive (accelerating) area under the graph is equal to the negative (decelerating) area for stability of a system. This condition is known as the equal area criterion. From **Figure 25**, it is seen that the point a corresponding δ_0 represents the steady-state operating point or equilibrium point. at this point, the machine's mechanical input power and electrical output power are equal, $P_{m0} = P_{e0}$. Consider a sudden increase in the input power of the machine as represented by the line P_{m1}. As a result, the machine's accelerating power will increase. which increases the power angle. Therefore, the rotor will move in the direction of point c. due to increasing energy in the rotor, to get to point c, the power and rotor angle will keep increasing. As a result, the rotor's mechanical input power will decrease, and the rotor will slow down at synchronous speed until it reaches the steady-state operating point, indicated by torque angle δ_2 or point b. For stability of a system, an equal area criterion requires the following condition.

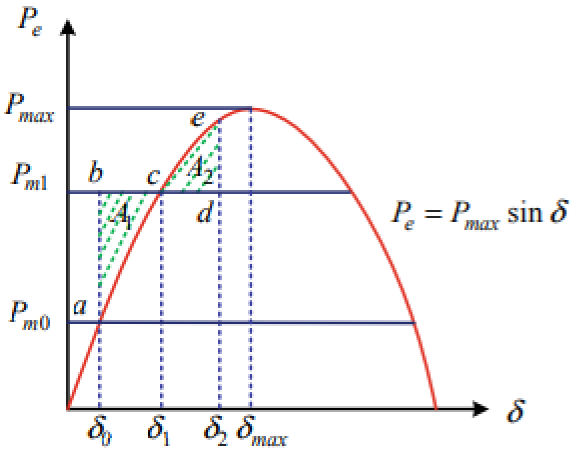


Figure 25 Power curve for an equal area criterion[20]

$$\text{Area } A_1 = \text{Area } A_2 \tag{2.82}$$

$$\int_{\delta_0}^{\delta_1} (P_m - P_{\max} \sin\ \delta) d\delta = \int_{\delta_1}^{\delta_2} (P_{\max} \sin\ \delta - P_m) d\delta \tag{2.83}$$

$$P_m(\delta_1 - \delta_0) + P_{\max} |\cos\ \delta|_{\delta_0}^{\delta_1} = -P_{\max} |\cos\ \delta|_{\delta_1}^{\delta_2} - P_m(\delta_2 - \delta_1) \tag{2.84}$$

$$P_m(\delta_1 - \delta_0 + \delta_2 - \delta_1) + P_{\max}(\cos\ \delta_1 - \cos\ \delta_0) = P_{\max}(\cos\ \delta_1 - \cos\ \delta_2) \tag{2.85}$$

$$P_m(\delta_2 - \delta_0) = P_{\max}(\cos\ \delta_0 - \cos\ \delta_2) \tag{2.86}$$

Substituting the expression $P_m = P_{\max} \sin \delta_1$ into Eq. **(2.86)** yields,

$$P_{\max}(\delta_2 - \delta_0)\sin\ \delta_1 = P_{\max}(\cos\ \delta_0 - \cos\ \delta_2) \tag{2.87}$$

$$(\delta_2 - \delta_0)\sin\ \delta_1 = \cos\ \delta_0 - \cos\ \delta_2 \tag{2.88}$$

$$(\delta_2 - \delta_0)\sin\ \delta_1 + \cos\ \delta_2 = \cos\ \delta_0 \tag{2.89}$$

From Eq. **(2.89)**, it is seen that the angle δ_2 can be calculated if the angles δ_0 and δ_1 are known.

2.8 System disturbances that can cause instability:

The most common disturbances that produce instability in industrial power systems are (not necessarily in order of probability):

- Short circuits
- Loss of a tie circuit to a public utility
- Loss of a portion of on-site generation
- Starting a motor that is large relative to a system generating capacity
- Switching operations
- Impact loading on motors
- sudden decrease in electrical load on generators [21]

2.9 The factors can affect transient stability:

- System Impedance which must include the transient reactance of all generating units. This affects phase angles and the flow of synchronizing power.
- Duration of the fault chosen as the criterion for stability. Duration will be dependent upon the circuit breaker speeds and the relay schemes used.
- Generator loadings prior to the fault which will determine the internal voltages and the change in output.
- System loading which will determine the phase angles among the various internal voltages of the generators.[22]

2.10 Conclusion:

In conclusion, power system stability is essential for ensuring a reliable and uninterrupted supply of electricity to consumers. This chapter presents the concepts of transient stability, their classifications, and some equations related to transient stability.

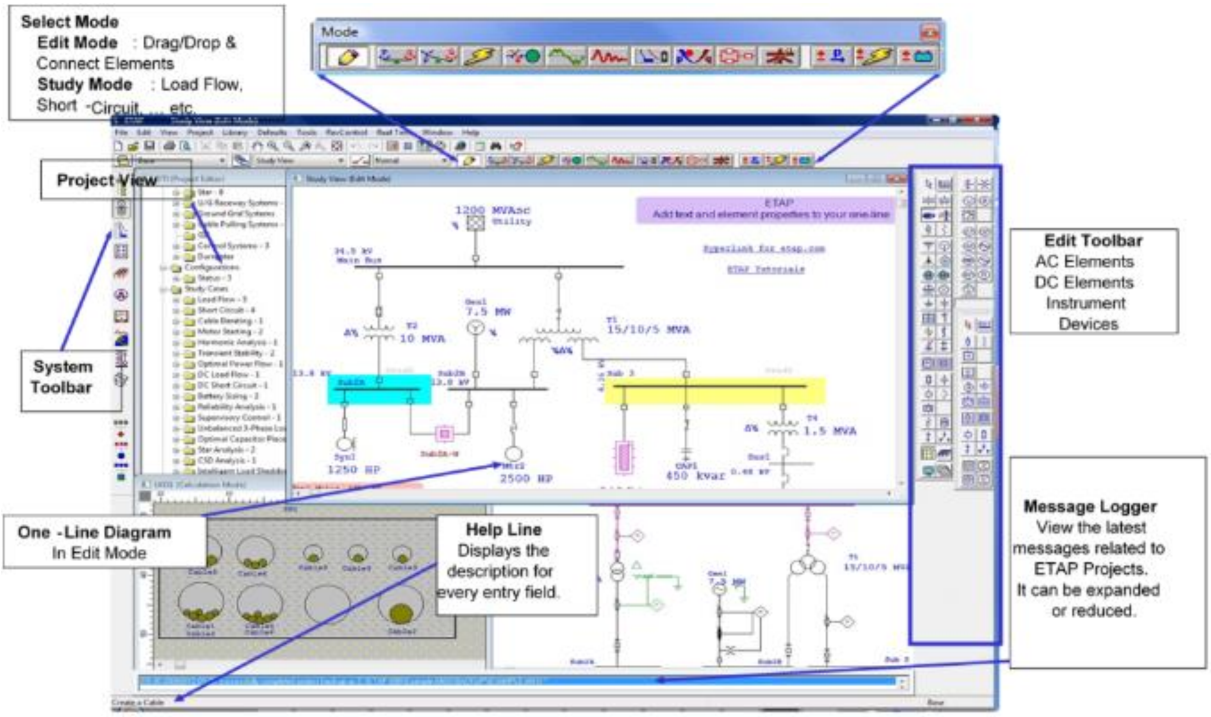
Chapter 3: ETAP simulation of power system stability study

3.1 Introduction to Etap software:

ETAP (Electrical Transient Analyzer Program) is a full-spectrum analytical engineering software developed by Operation Technology Inc. The software specializes in the analysis, simulation, monitoring, control, optimization, and automation of electrical power systems. ETAP software offers the most comprehensive and integrated suite of power system enterprise solutions that spans from modelling to operation. The ETAP Software provides a good interface for performing rigorous analysis on electrical power systems and is one of the best in Electrical Transient analysis software. Its integration with Microsoft Excel is also one of its many amazing features.

Figure 26 ETAP Features Overview

The ETAP Software provides an easy-to-use, user-friendly environment along with a comprehensive user manual that helps users through any problem encountered during simulation. The Basic interface of ETAP is shown in the Figure 27 below.



Select Mode
Edit Mode : Drag/Drop & Connect Elements
Study Mode : Load Flow, Short -Circuit, ... etc.

One -Line Diagram In Edit Mode

Help Line Displays the description for every entry field.

Edit Toolbar AC Elements DC Elements Instrument Devices

Message Logger View the latest messages related to ETAP Projects. It can be expanded or reduced.

Figure 27 ETAP GUI-based User Interface

3.1.1 Menu bar:

File Edit View Project Library Warehouse Rules Defaults Tools RevControl Real-Time Window Help

The Menu bar contains a comprehensive list of menu options. Each option activates a drop-down list of commands such as File operations, Printing, Database Conversions, Data Exchange, OLE objects, Project Standards, Project Settings and Project Options, Libraries, Defaults, Annotation Fonts, Base and Revision Data, and more.

3.1.2 Project toolbar:

The Project toolbar contains buttons that provide shortcuts for many commonly used functions. Those functions are: Create Projects, Open Projects, Save Projects, Print, Print Preview, Cut, Copy, Paste, Pan, Zoom, Undo, Redo, Text Box, Grid Display, Continuity Check, Themes, Get Template, Add to OLV Template, Hyperlink, Power Calculator, Find, and Help.

3.1.3 Edit toolbars:

The Edit toolbars are active when you are in Edit Mode. You can click or double-click to select, drag and drop AC, DC, and instrument elements on the one-line diagrams. Additionally, you can perform the following functions:[23]

- View & Print Customizable Output Reports (Text & Crystal Reports)
- Change Display Options

- Access Schedule Report Manager
- Add New Ground Grid Systems
- Add Composite Networks & Composite Motors

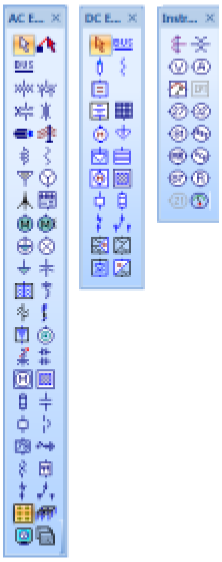


Figure 28 ETAP Edit Toolbars

3.1.4 Study modes:

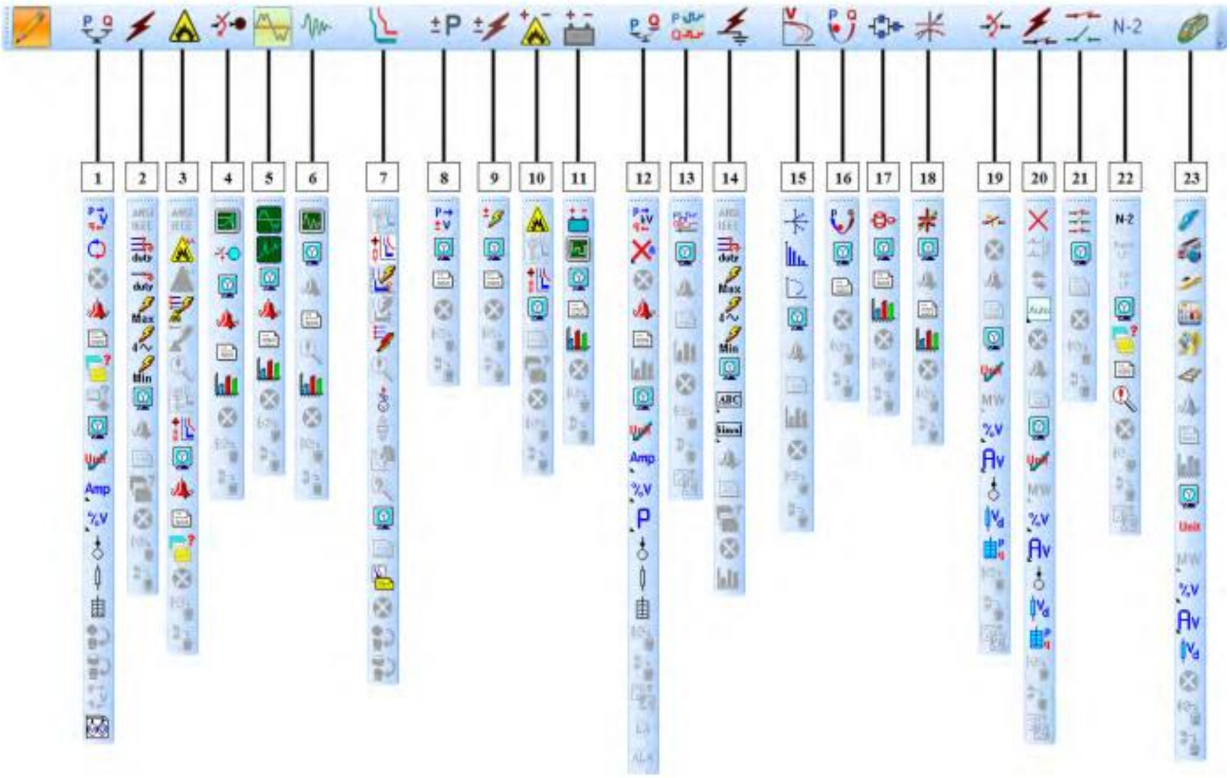


Figure 29 ETAP Study Modes

ETAP provides the following study modes directly from the one-line diagram:

1. Load Flow Analysis
2. Short-Circuit Analysis

3. Arc Flash Analysis
4. Motor Acceleration Analysis
5. Harmonic Analysis
6. Transient Stability Analysis
7. Star – Protective Device Coordination
8. DC Load Flow Analysis
9. DC Short-Circuit Analysis
10. . DC Arc Flash Analysis
11. Battery Sizing and Discharge Calculations
12. Unbalanced Load Flow Analysis
13. Time Domain Load Flow Analysis
14. Unbalanced Short Circuit Analysis
15. Voltage Stability Analysis
16. Optimal Power Flow Analysis
17. Reliability Assessment
18. Optimal Capacitor Placement
19. Switching Optimization
20. FMSR Analysis

3.2 Schematic diagram of the power system network:

In this system, five bus system from the network feeder 13.8KV line comes to the utility bus. Then it separates into two lines. The two lines go to T1, T2, 20 MVA transformers where voltage steps down to 4.16 KV. Then it gives supply two buses through a circuit breaker. From bus 2 one line go to lumped load. The second line goes to the 6 MV generator working as a standby. The third line goes through a cable to 3 MVA transformer step down to 0.48 KV bus 6. From bus 3 one line go to lumped load. The second line goes through a cable to 3 MVA transformer step down to 0.48 KV bus 7. Bus 6 and bus 7 supply serval load (synchronous motor, induction machine, lumped load), and also the tow bus (6,7) is connected with low voltage circuit breaker (LVCB).

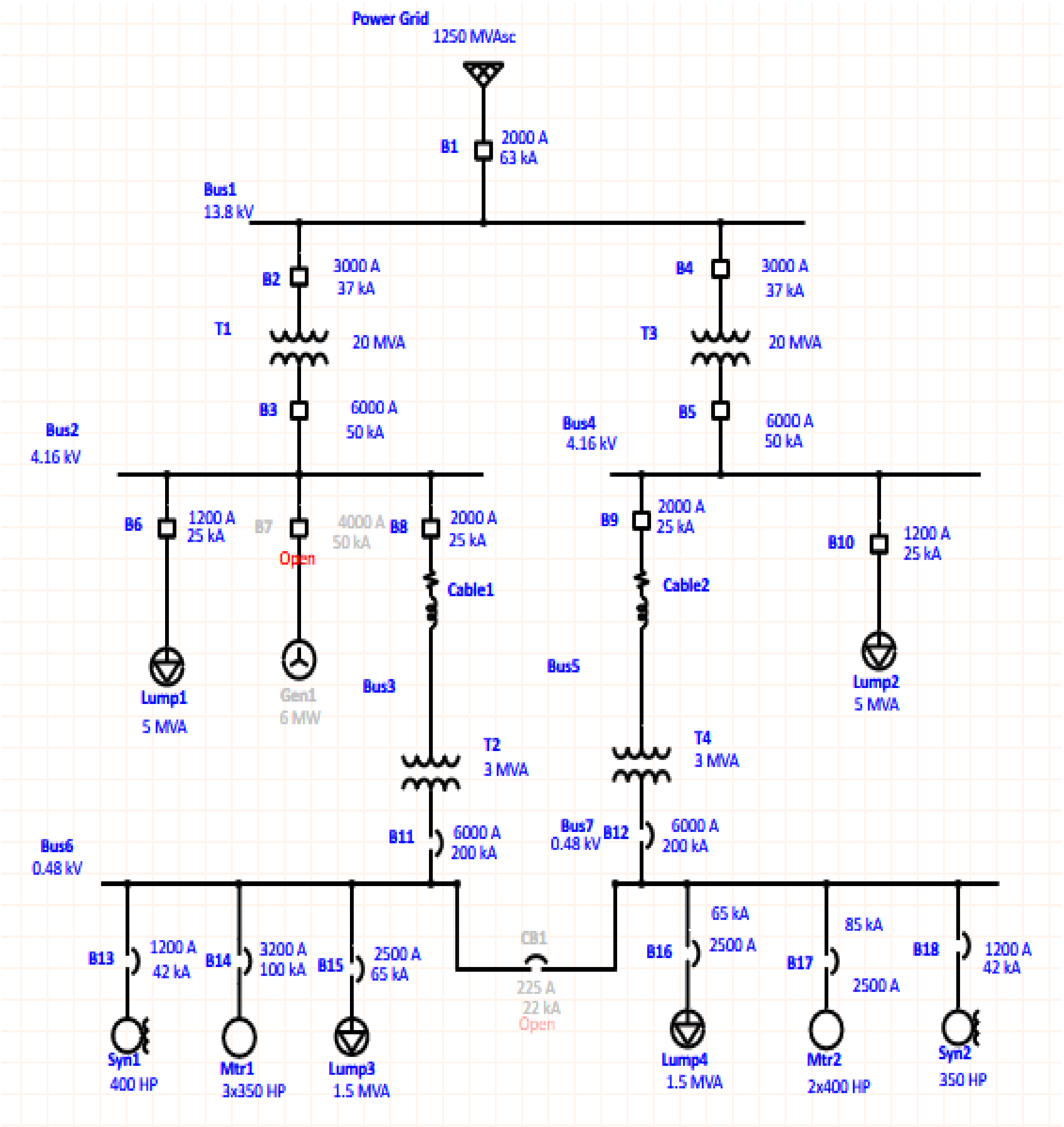


Figure 30 Schematic diagram of the power system network

3.3 Power flow analysis:

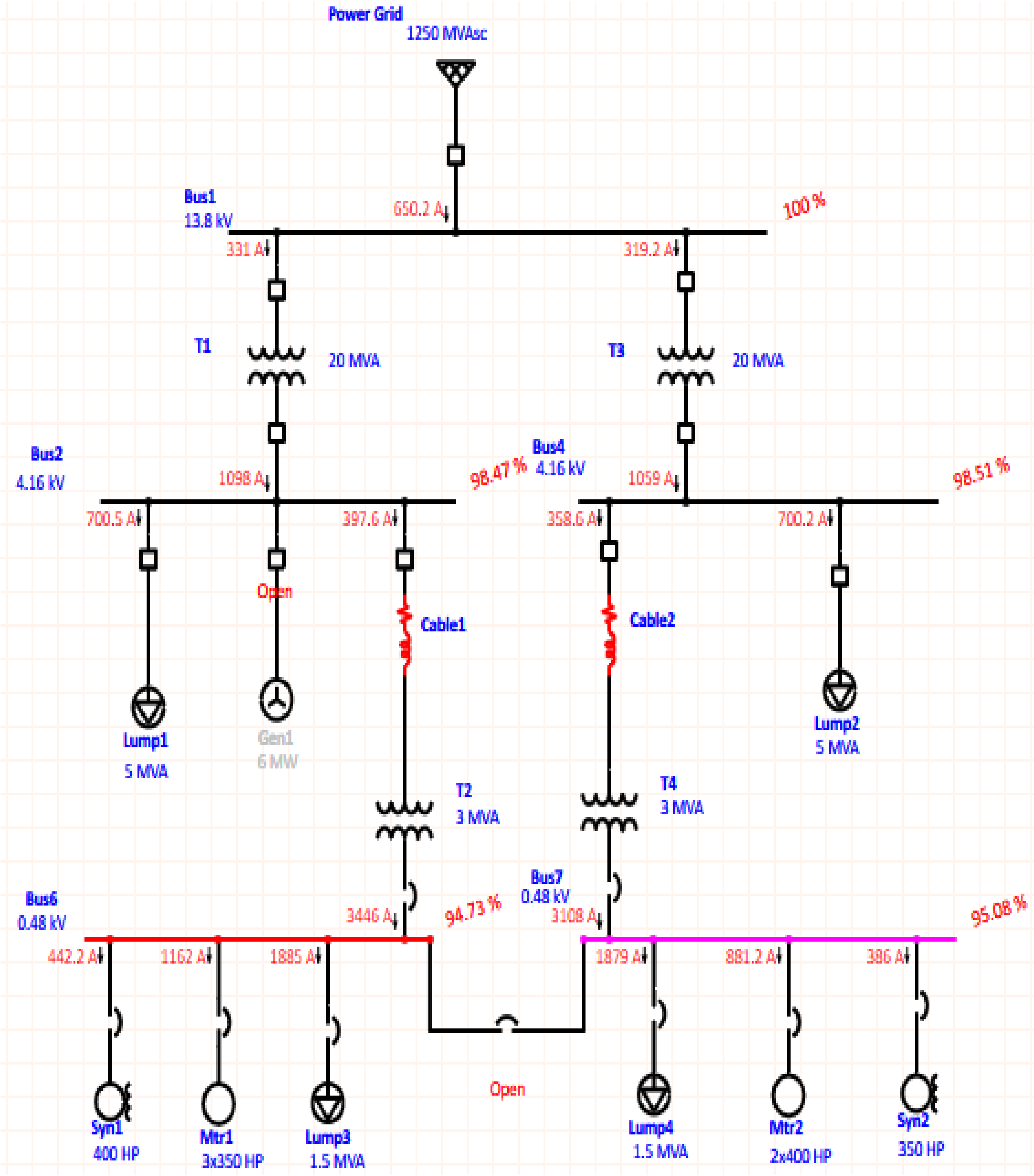
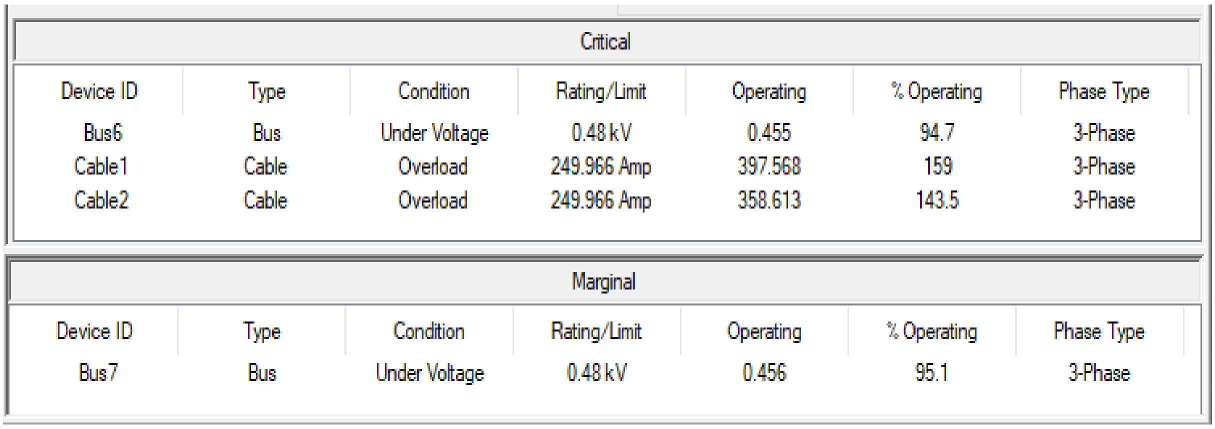


Figure 31 Schematic diagram of power flow analysis

after doing a power flow analysis on the system, it was found there cable1 and cable2 were facing an overload. also, it was found that bus 6 was facing under-voltage with a voltage level 94.7% of the rated voltage either the bus7 had the same problem that was facing under-voltage with a voltage level 95.08% as shown in Figure 31

3.3.1 ETAP alert view:

During the load flow analysis, the ETAP gives the different alerts for the condition to be solved on urgent basis. It shows the operating condition of device and shows whether the condition is marginal or critical.



Critical

Device ID	Type	Condition	Rating/Limit	Operating	% Operating	Phase Type
Bus6	Bus	Under Voltage	0.48 kV	0.455	94.7	3-Phase
Cable1	Cable	Overload	249.966 Amp	397.568	159	3-Phase
Cable2	Cable	Overload	249.966 Amp	358.613	143.5	3-Phase

Marginal

Device ID	Type	Condition	Rating/Limit	Operating	% Operating	Phase Type
Bus7	Bus	Under Voltage	0.48 kV	0.456	95.1	3-Phase

Solution the problem of the power flow analysis:

The problem of the under voltage for bus 6, bus7, and can be solved by placing the capacitor banks in parallel with the three-phase feeders. These capacitor banks produce the leading current and absorb the reactive power of the bus. to find the capacitor bank rating. The rating of the capacitor bank is calculated by using the following formula, which ETAP can automatically solve it by use the optimal capacitor placement mode.

Rating of Capacitor Bank MVAr = MW * (Tan ф1 – Tan ф2)

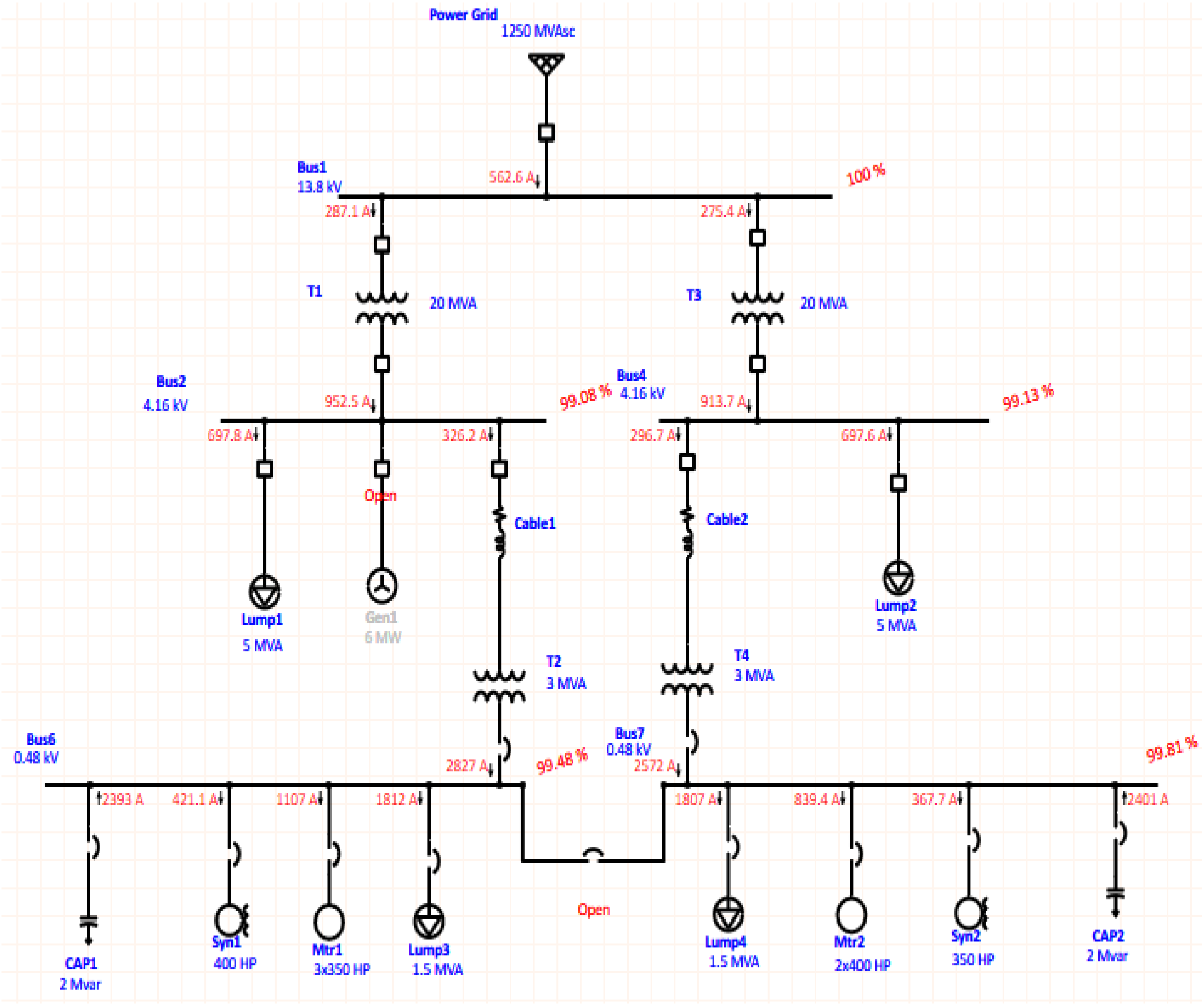
Where ф1 and ф2 can be calculated as: Cos ф1 = Existing Power Factor, Cos ф2 = Required Power Factor

For the rating of breakers (bus6, bus7) of both capacitors that we have need it later in the short circuit analysis, the is as follower

$I_{FL}=\frac{Q}{\sqrt{3}(V)}$ where: I_{FL} full load current (KA), Q: reactive power (KVA),

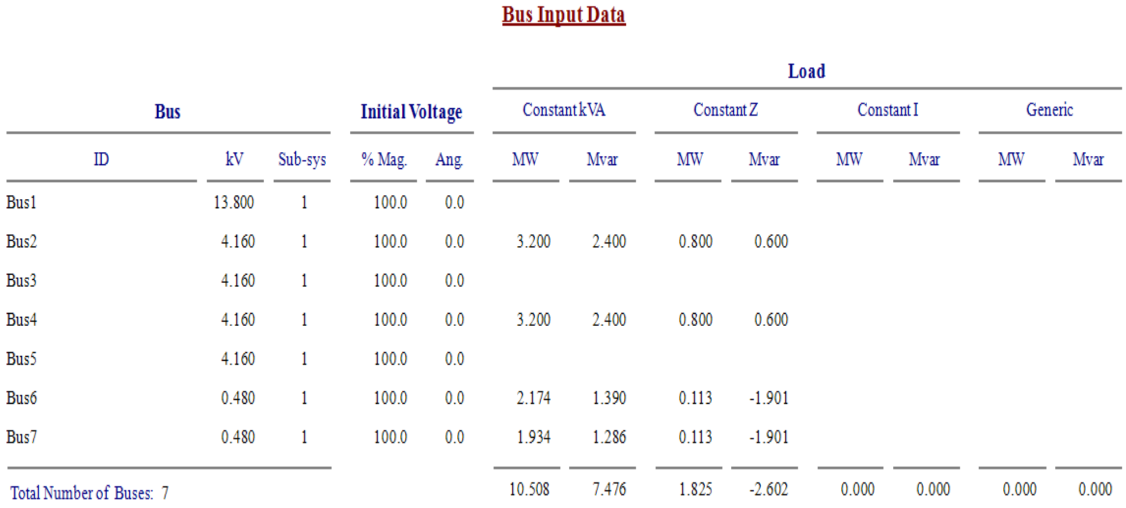
V: voltage (KV)

The other problem is in cable 1 and cable 2 they have an overvoltage issue as we know the 3-phase circuit requires 4 wires (3 conductors and 1 neutral) so then we have to change the no. of conductor/phase to 4.



3.3.2 Power flow ETAP results:

3.3.2.1 Production, load, and BUS voltage data:

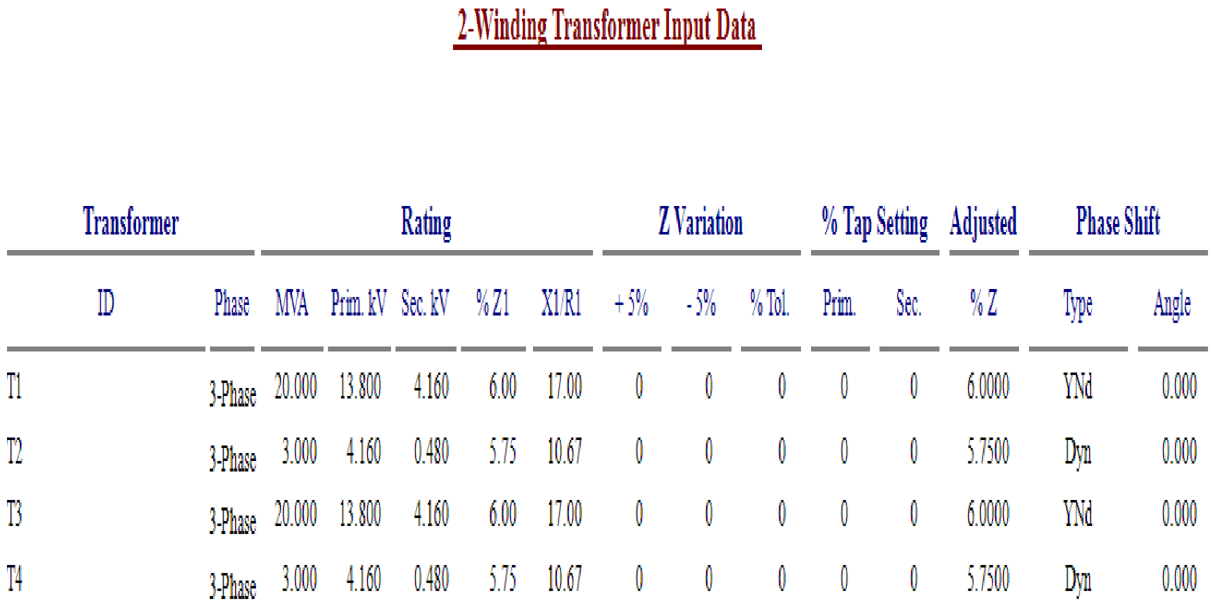


Bus Input Data

Bus			Initial Voltage		Load							
					Constant kVA		Constant Z		Constant I		Generic	
ID	kV	Sub-sys	% Mag.	Ang.	MW	Mvar	MW	Mvar	MW	Mvar	MW	Mvar
Bus1	13.800	1	100.0	0.0								
Bus2	4.160	1	100.0	0.0	3.200	2.400	0.800	0.600				
Bus3	4.160	1	100.0	0.0								
Bus4	4.160	1	100.0	0.0	3.200	2.400	0.800	0.600				
Bus5	4.160	1	100.0	0.0								
Bus6	0.480	1	100.0	0.0	2.174	1.390	0.113	-1.901				
Bus7	0.480	1	100.0	0.0	1.934	1.286	0.113	-1.901				
Total Number of Buses: 7					10.508	7.476	1.825	-2.602	0.000	0.000	0.000	0.000

The data in shape correspond to the different voltage, and power in MW and in MVAR at bus level.

3.3.2.2 Transformers data:

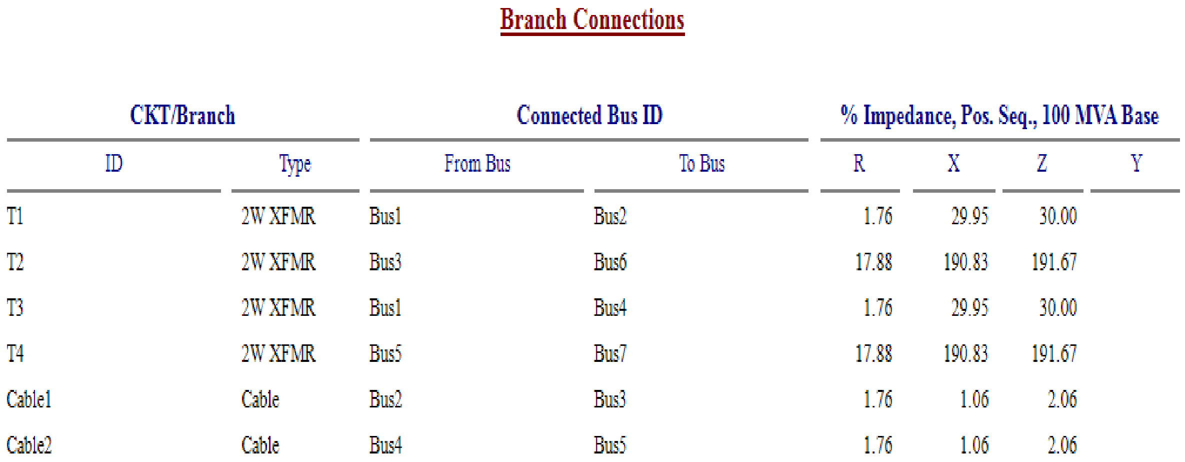


2-Winding Transformer Input Data

Transformer	Rating						Z Variation			% Tap Setting		Adjusted	Phase Shift	
ID	Phase	MVA	Prim. kV	Sec. kV	% Z1	X1/R1	+ 5%	- 5%	% Tol.	Prim.	Sec.	% Z	Type	Angle
T1	3-Phase	20.000	13.800	4.160	6.00	17.00	0	0	0	0	0	6.0000	YNd	0.000
T2	3-Phase	3.000	4.160	0.480	5.75	10.67	0	0	0	0	0	5.7500	Dyn	0.000
T3	3-Phase	20.000	13.800	4.160	6.00	17.00	0	0	0	0	0	6.0000	YNd	0.000
T4	3-Phase	3.000	4.160	0.480	5.75	10.67	0	0	0	0	0	5.7500	Dyn	0.000

This table shows the different data of 2-winding transformers.

Connections of the branches or branches and the value (resistance, reactance and impedance):

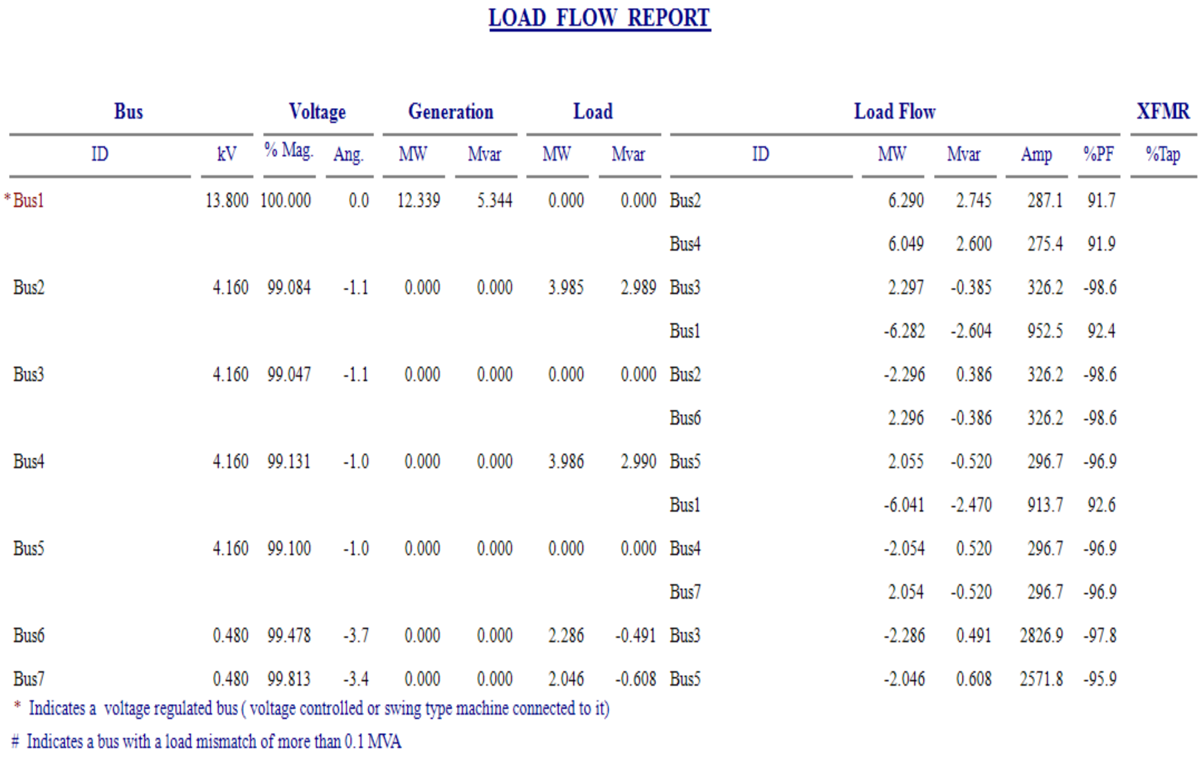


Branch Connections

CKT/Branch		Connected Bus ID		% Impedance, Pos. Seq., 100 MVA Base			
ID	Type	From Bus	To Bus	R	X	Z	Y
T1	2W XFMR	Bus1	Bus2	1.76	29.95	30.00	
T2	2W XFMR	Bus3	Bus6	17.88	190.83	191.67	
T3	2W XFMR	Bus1	Bus4	1.76	29.95	30.00	
T4	2W XFMR	Bus5	Bus7	17.88	190.83	191.67	
Cable1	Cable	Bus2	Bus3	1.76	1.06	2.06	
Cable2	Cable	Bus4	Bus5	1.76	1.06	2.06	

This table shows the connection between the branches and the value of the (resistance, reactance and impedance).by example taking the tapping transformer T4 it passes from bus5 to bus7 and his (resistance is 17.88, reactance 190.83, impedance 191.67)

3.3.2.3 Load flow report:



LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
*Bus1	13.800	100.000	0.0	12.339	5.344	0.000	0.000	Bus2	6.290	2.745	287.1	91.7	
								Bus4	6.049	2.600	275.4	91.9	
Bus2	4.160	99.084	-1.1	0.000	0.000	3.985	2.989	Bus3	2.297	-0.385	326.2	-98.6	
								Bus1	-6.282	-2.604	952.5	92.4	
Bus3	4.160	99.047	-1.1	0.000	0.000	0.000	0.000	Bus2	-2.296	0.386	326.2	-98.6	
								Bus6	2.296	-0.386	326.2	-98.6	
Bus4	4.160	99.131	-1.0	0.000	0.000	3.986	2.990	Bus5	2.055	-0.520	296.7	-96.9	
								Bus1	-6.041	-2.470	913.7	92.6	
Bus5	4.160	99.100	-1.0	0.000	0.000	0.000	0.000	Bus4	-2.054	0.520	296.7	-96.9	
								Bus7	2.054	-0.520	296.7	-96.9	
Bus6	0.480	99.478	-3.7	0.000	0.000	2.286	-0.491	Bus3	-2.286	0.491	2826.9	-97.8	
Bus7	0.480	99.813	-3.4	0.000	0.000	2.046	-0.608	Bus5	-2.046	0.608	2571.8	-95.9	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

\# Indicates a bus with a load mismatch of more than 0.1 MVA

This table shows the results of the power flow. by taking the example on bus1 he indicates voltage regulation (controlled voltage), its voltage is 13.8 KV, his power in MW is 12.339 and in MVAR is 5.344, load flow is 6.290 MW, current is 287.1 A, power factor 91.7%, For the other buses, each differs in its own results.

3.4 Short circuit analysis:

To find out how much short circuit current the system is capable of producing and to compare it to the interrupting rating of the over-current protective devices, a short circuit current analysis is used. To fully understand how it works, we had to introduce certain faults at the network, how will the network behave and try to find a remedy in case of abnormal functioning of the network, so with adding faults on bus 6, the figure will show the following.

3.4.1.1 The first case:

Analysis 3 phase fault on bus 6:

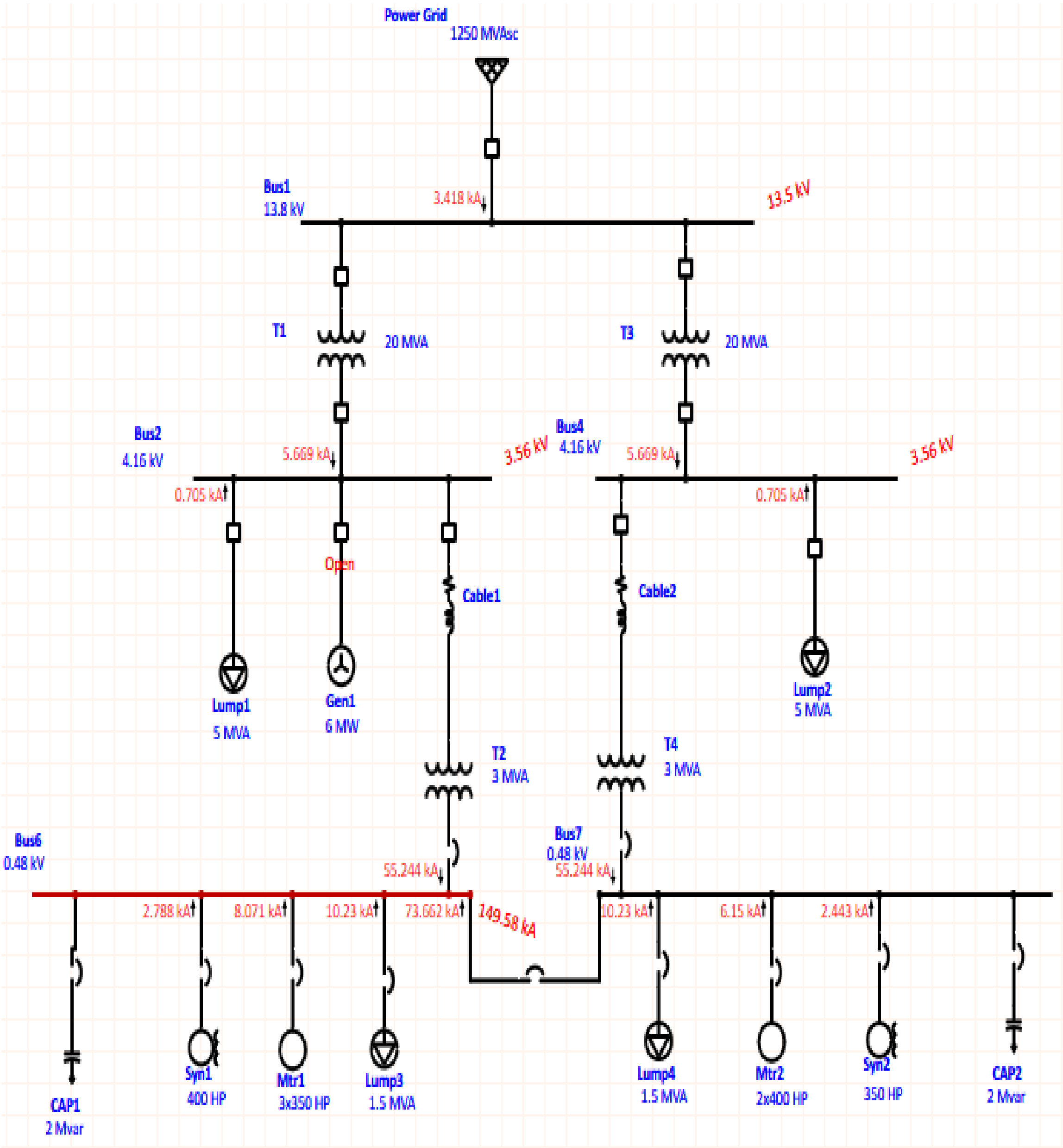
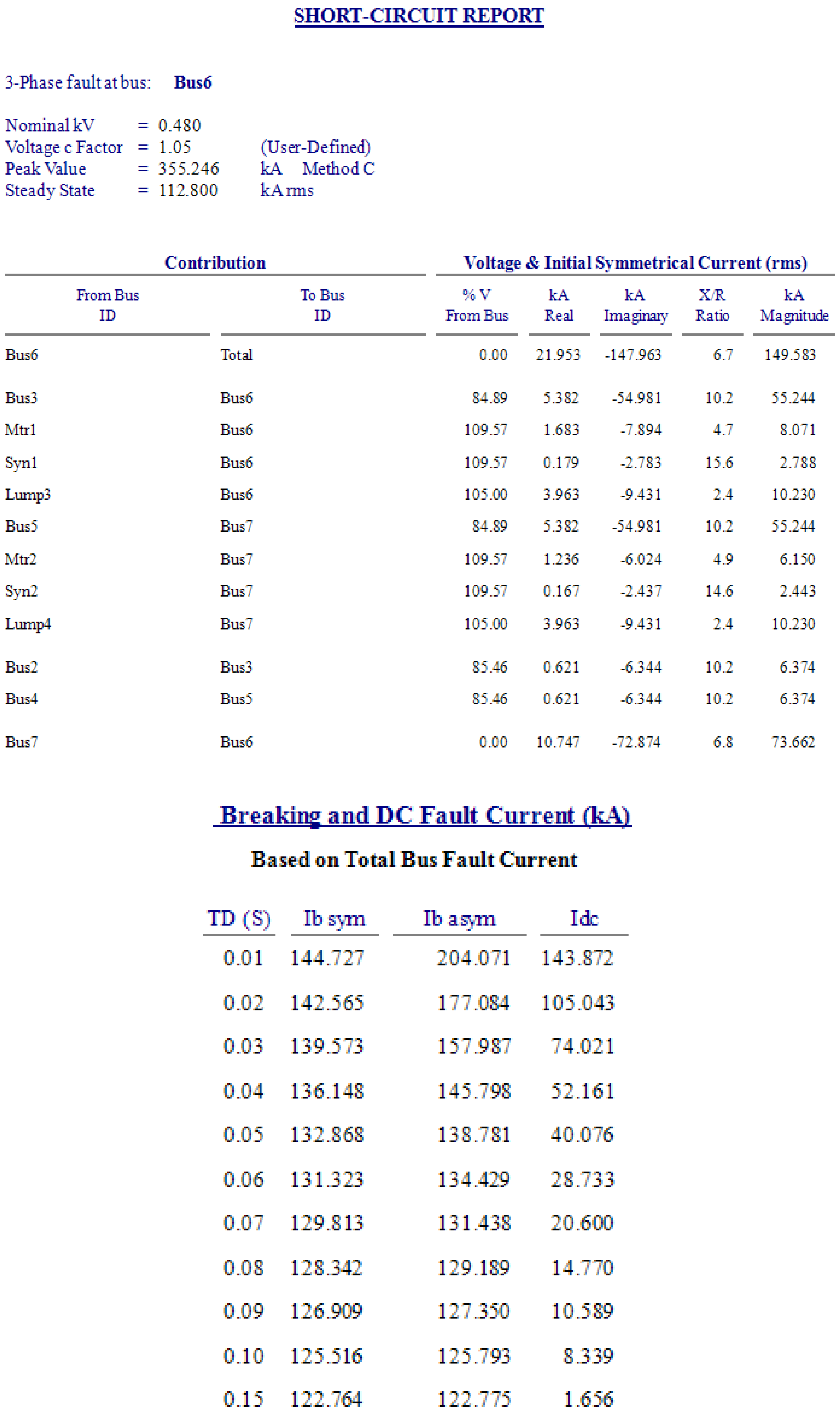


Figure 32 Short Circuit Analysis 3 phase device duty IEC on bus 6



SHORT-CIRCUIT REPORT

3-Phase fault at bus: **Bus6**

Nominal kV = 0.480
Voltage c Factor = 1.05 (User-Defined)
Peak Value = 355.246 kA Method C
Steady State = 112.800 kA rms

Contribution		Voltage & Initial Symmetrical Current (rms)				
From Bus ID	To Bus ID	% V From Bus	kA Real	kA Imaginary	X/R Ratio	kA Magnitude
Bus6	Total	0.00	21.953	-147.963	6.7	149.583
Bus3	Bus6	84.89	5.382	-54.981	10.2	55.244
Mtr1	Bus6	109.57	1.683	-7.894	4.7	8.071
Syn1	Bus6	109.57	0.179	-2.783	15.6	2.788
Lump3	Bus6	105.00	3.963	-9.431	2.4	10.230
Bus5	Bus7	84.89	5.382	-54.981	10.2	55.244
Mtr2	Bus7	109.57	1.236	-6.024	4.9	6.150
Syn2	Bus7	109.57	0.167	-2.437	14.6	2.443
Lump4	Bus7	105.00	3.963	-9.431	2.4	10.230
Bus2	Bus3	85.46	0.621	-6.344	10.2	6.374
Bus4	Bus5	85.46	0.621	-6.344	10.2	6.374
Bus7	Bus6	0.00	10.747	-72.874	6.8	73.662

Breaking and DC Fault Current (kA)

Based on Total Bus Fault Current

TD (S)	Ib sym	Ib asym	Idc
0.01	144.727	204.071	143.872
0.02	142.565	177.084	105.043
0.03	139.573	157.987	74.021
0.04	136.148	145.798	52.161
0.05	132.868	138.781	40.076
0.06	131.323	134.429	28.733
0.07	129.813	131.438	20.600
0.08	128.342	129.189	14.770
0.09	126.909	127.350	10.589
0.10	125.516	125.793	8.339
0.15	122.764	122.775	1.656

In the event of an outage or fault, the coupling circuit breaker will be open B8 and the other bus provides power until maintenance of the bus 6.

3.4.1.2 The second case:

Analysis 3 phase fault on the source bus1

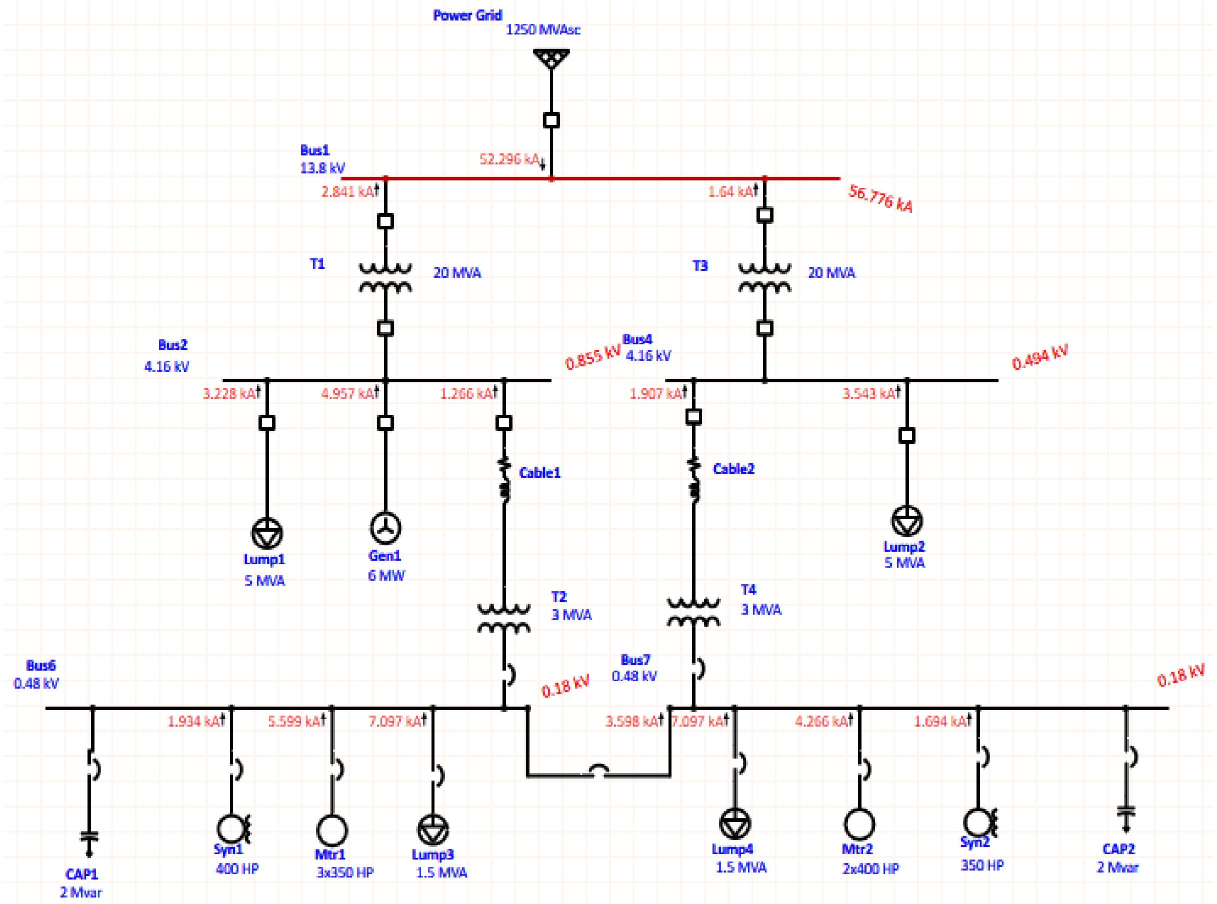
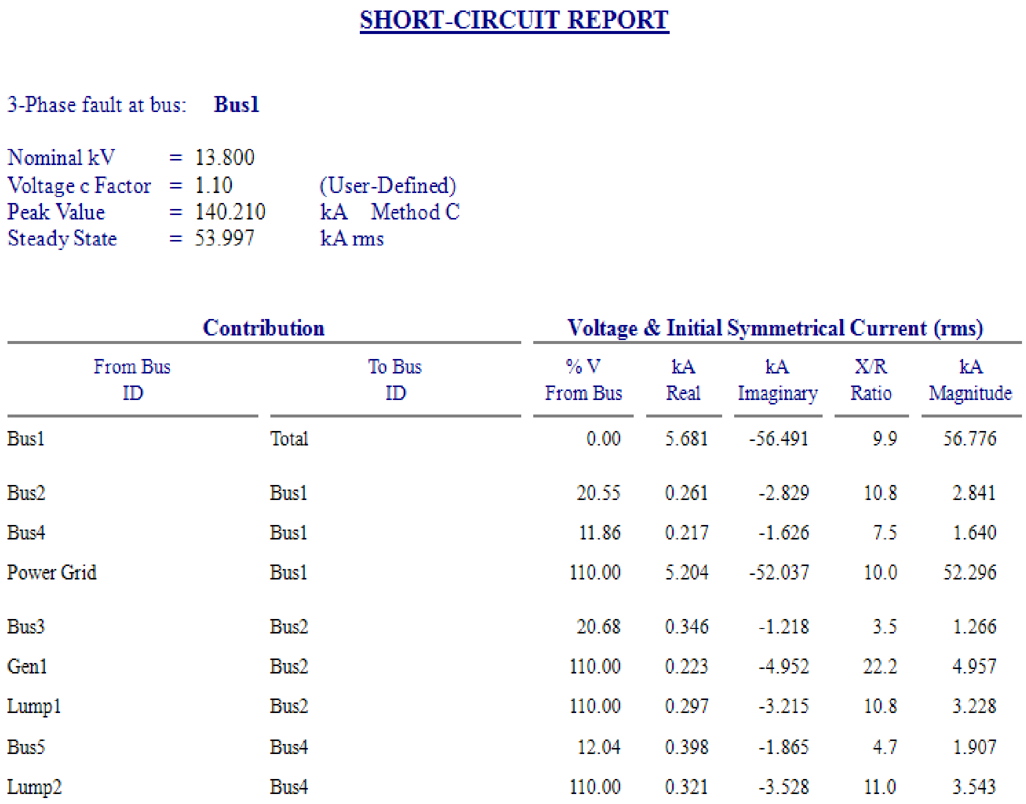


Figure 33 Short Circuit Analysis 3 phase device duty IEC on bus 1

In the event of a fault on a source, the other source provides all the power until source 1 is functional. The propagation of the fault current according to the shape is high-speed as a function of time, which leads to rapid isolation of the source via the protective devices.

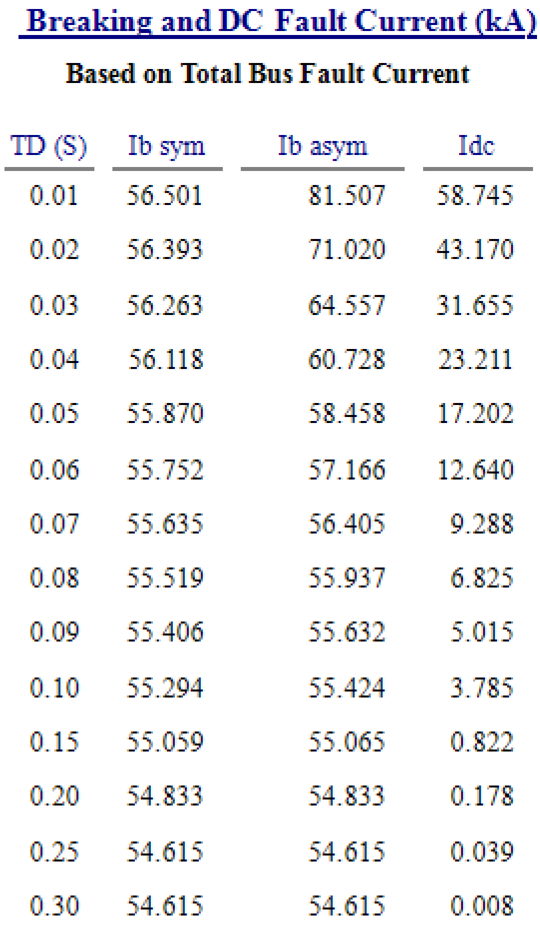


SHORT-CIRCUIT REPORT

3-Phase fault at bus: **Bus1**

Nominal kV = 13.800
Voltage c Factor = 1.10 (User-Defined)
Peak Value = 140.210 kA Method C
Steady State = 53.997 kA rms

Contribution		Voltage & Initial Symmetrical Current (rms)				
From Bus ID	To Bus ID	% V From Bus	kA Real	kA Imaginary	X/R Ratio	kA Magnitude
Bus1	Total	0.00	5.681	-56.491	9.9	56.776
Bus2	Bus1	20.55	0.261	-2.829	10.8	2.841
Bus4	Bus1	11.86	0.217	-1.626	7.5	1.640
Power Grid	Bus1	110.00	5.204	-52.037	10.0	52.296
Bus3	Bus2	20.68	0.346	-1.218	3.5	1.266
Gen1	Bus2	110.00	0.223	-4.952	22.2	4.957
Lump1	Bus2	110.00	0.297	-3.215	10.8	3.228
Bus5	Bus4	12.04	0.398	-1.865	4.7	1.907
Lump2	Bus4	110.00	0.321	-3.528	11.0	3.543



Breaking and DC Fault Current (kA)

Based on Total Bus Fault Current

TD (S)	Ib sym	Ib asym	Idc
0.01	56.501	81.507	58.745
0.02	56.393	71.020	43.170
0.03	56.263	64.557	31.655
0.04	56.118	60.728	23.211
0.05	55.870	58.458	17.202
0.06	55.752	57.166	12.640
0.07	55.635	56.405	9.288
0.08	55.519	55.937	6.825
0.09	55.406	55.632	5.015
0.10	55.294	55.424	3.785
0.15	55.059	55.065	0.822
0.20	54.833	54.833	0.178
0.25	54.615	54.615	0.039
0.30	54.615	54.615	0.008

3.5 Transient stability analysis:

The intention of the transient stability analysis is to examine the system, whether the defined disturbance, i.e., if the system is affected by the fault. the dynamically responsive system and stability restrictions, during transient and short circuit, are simulated to study the performance stability of the system disturbances.

When the standby generator is put in service in the system, The transient stability is analysed for 7 bus system which is shown in Figure 30, The three-phase fault is created at bus 2 for 0.200 seconds and is cleared after 0.275 seconds with the help of transient stability study case editor. At starting there will not be any power oscillations in the output and the system will be in the normal condition, the machine runs at synchronous speed. When time is at 0.200 seconds there will be oscillations in the output, when time is at 0.275 seconds the fault at the bus is cleared so the electromechanical oscillations are reduced and the system comes back to normal condition. in which the system regains its synchronism. The figures below show the result of this operation

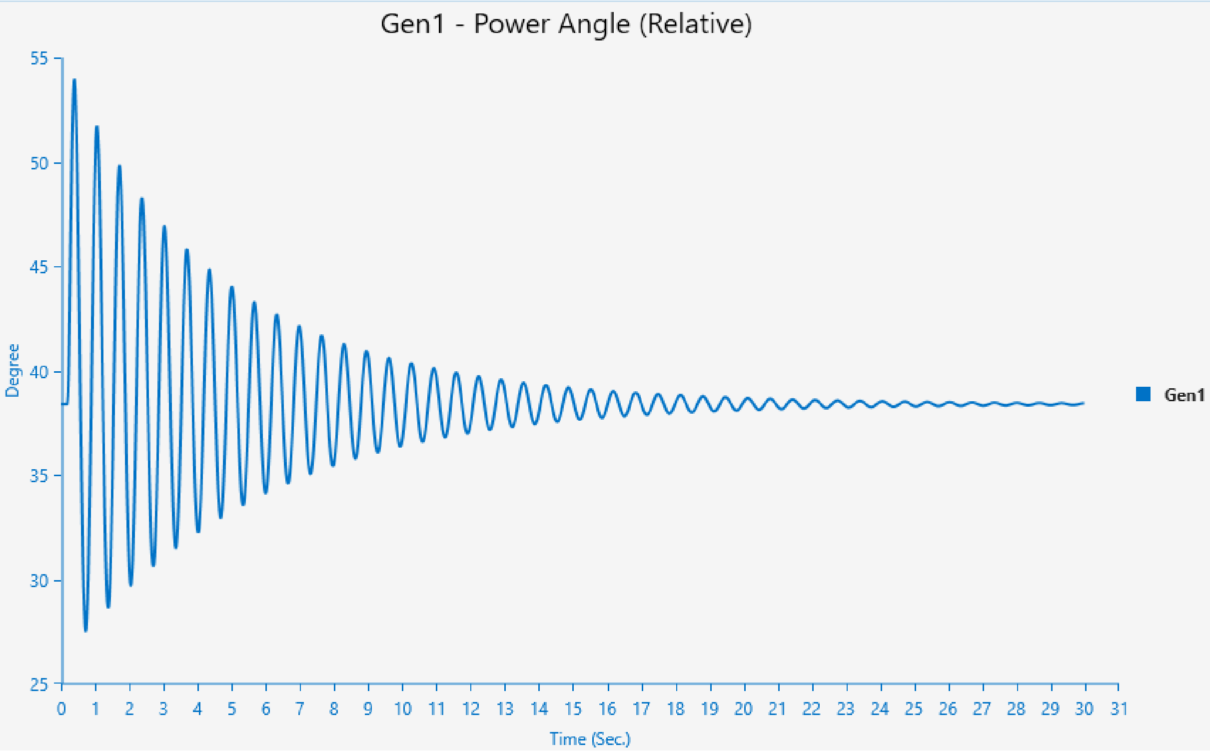


Figure 34 Generator relative power angle

Figure 34 shows generator relative power angle V_s time. The oscillation in the output is reduced when the fault is cleared and steady state power is improved.

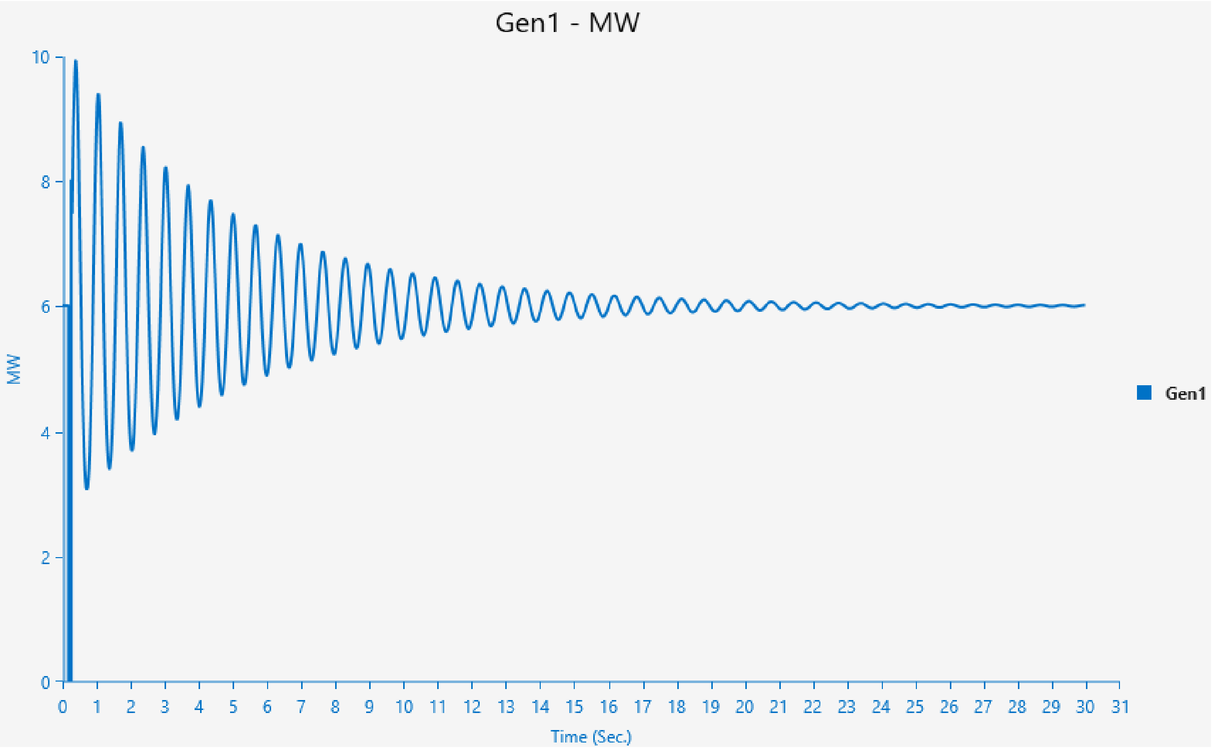


Figure 35 Generator Electrical Power

Error! Reference source not found. shows generator electrical power V_s time. The electromechanical oscillations are reduced and the power swing is damped out and the system attains stable condition.

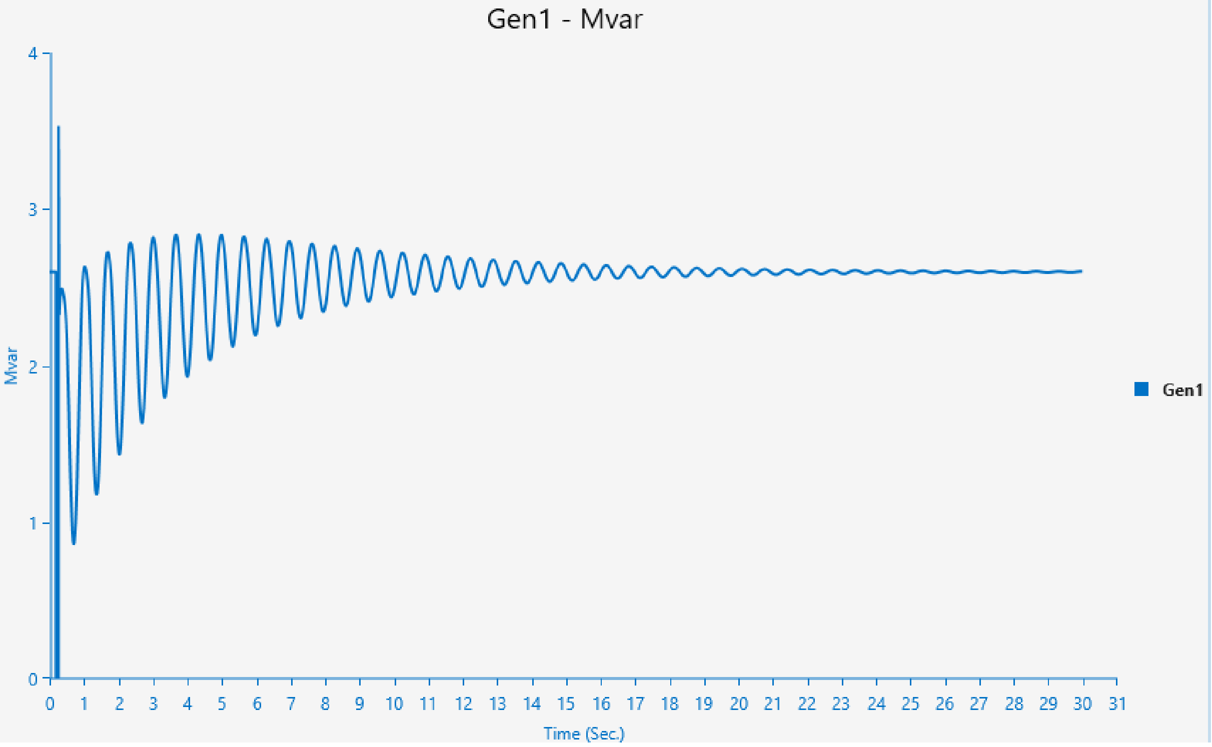


Figure 36 Generator Reactive power

Figure 36 shows generator reactive power V_s time. The oscillation in the output is reduced when the fault is cleared and steady state power is improved.

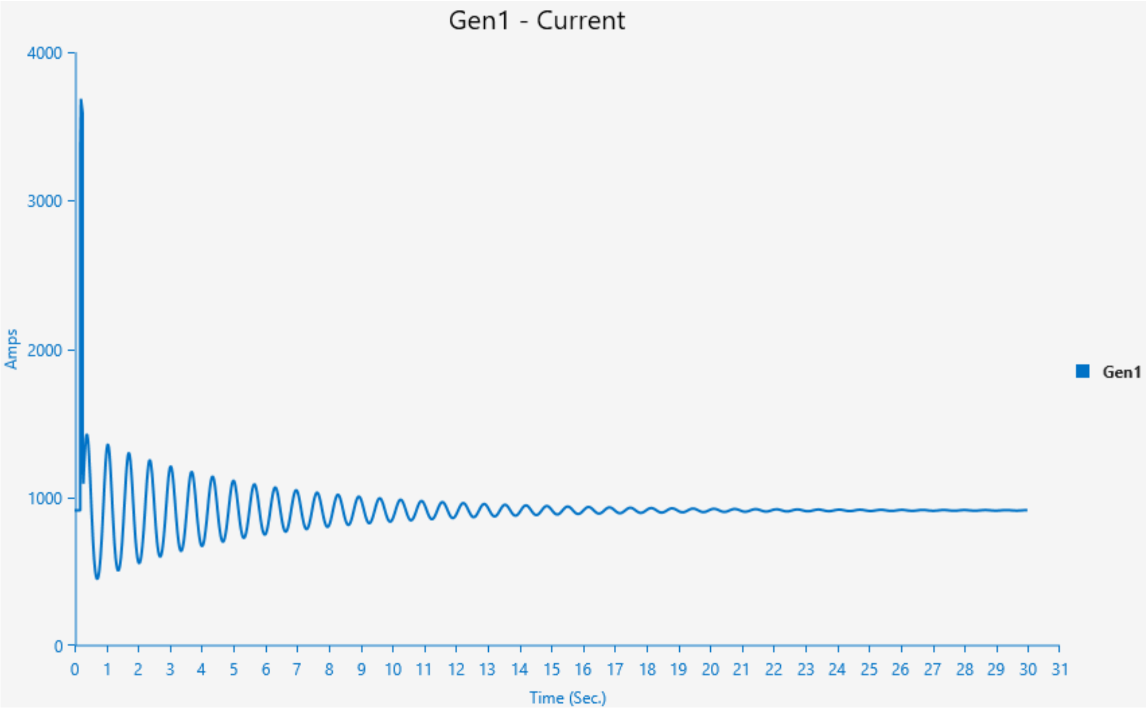


Figure 37 Generator Terminal Current

Figure 37 shows terminal current Vs time. The oscillations in the terminal current output are reduced and the system reaches stable operating condition at 2.500 seconds.

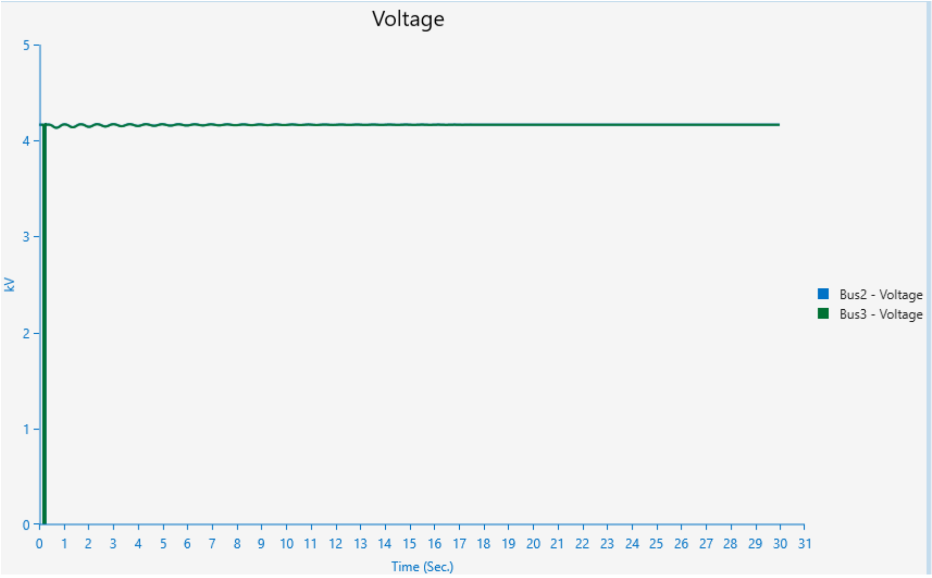


Figure 38 Bus Voltage

Figure 38: shows bus voltage, which indicates that the fault bus voltage decreases during the transient period and recovers once when fault is cleared.

3.6 Conclusion:

This chapter presents the Simulated results of a network before the integration of renewable energy systems were presented using the ETAP program.

Chapter 4: Integration of Distributed energy resources (DERs) in power system

4.1 Introduction:

Global energy demand has been rising rapidly. Coal, oil, and gas are a few finite examples of traditional energy sources. as a result, it is essential that we take care of our current energy supplies and look into new ones. Solar and wind energy are the most promising for humanity among various kinds of renewable energy resources [24] . Renewable energy sources will form the foundation of the energy system in the future because of the abundance of available renewable energy. Renewable energy will eventually replace fossil fuels like coal, oil, and gas in our energy consumption patterns. In order to integrate a significant amount of renewable energy sources into the power system, The existing energy systems need to be reconfigured. The transformation depends on the intelligent power grid, often known as the smart grid (SG). In the future, distributed renewable energy sources (DERs), a strong power grid, flexible consumption, and intelligent power control systems will all be components of SG systems[25]. Distributed renewable energy sources (e.g., wind turbine, photovoltaic, etc.) and energy storage devices (e.g., battery, electric double layer capacitor, superconducting magnetic energy storage, etc.) are expected to be essential in developing the green SG system and supplying the world's energy needs[26]. The distributed generations (DGs) place generation on the distribution network or on the customer side of the meter, that is, near to the load[27]. The performance of distribution systems may be greatly improved by DGs; hence they should be promoted[28].

Rating of DGs: The maximum rating of the DG that may be connected to a distributed generation system depends on the distribution system's capacity, which is correlated with its voltage level. As a result, DG capacity might vary widely. DGs are divided into four main categories which are as follows [29]:

Micro. DG range: ~1 W < 5 kW;
Small. DG range: 5 kW < 5 MW;
Medium. DG range: 5 MW < 50 MW;
Large. DG range: 50 MW < ~300 MW.

Due to the various types of DGs, the generation of electric current can be either direct current (DC) or alternating current (AC). Photovoltaic, and batteries generate the DC which is suitable for both DC loads and DC SG. On the other side, a power electronics interface can convert DC to AC, which can then be used to connect to AC loads and the power grid. Other DGs, like wind turbines, produce AC that, in some cases, needs to be managed using modern power electronics equipment in order to achieve the regulated voltage[27].

4.2 Distributed generation resources:

photovoltaic (PV) energy, wind turbines, and other dispersed generating facilities are frequently located in remote locations, they need operating systems that are completely integrated into the transmission and distribution network[30]. The important goals of the integration of all types of power plants in the smart grid are reducing greenhouse gas emissions and overall costs. This is achieved through the use of modern technology and smart microgrid controllers and devices, which are expected to be used by distribution companies in the next generation of smart networks. Local generation, on-site generation, or distributed energy are other terms for distributed generation (DG), a method of generating power from a variety of small energy sources. The energy sources are directly connected to the medium voltage (MV) or low voltage (LV) distribution systems, instead of the systems of bulk power transfer. Various DG resource types are shown in **Error! Reference source not found.**

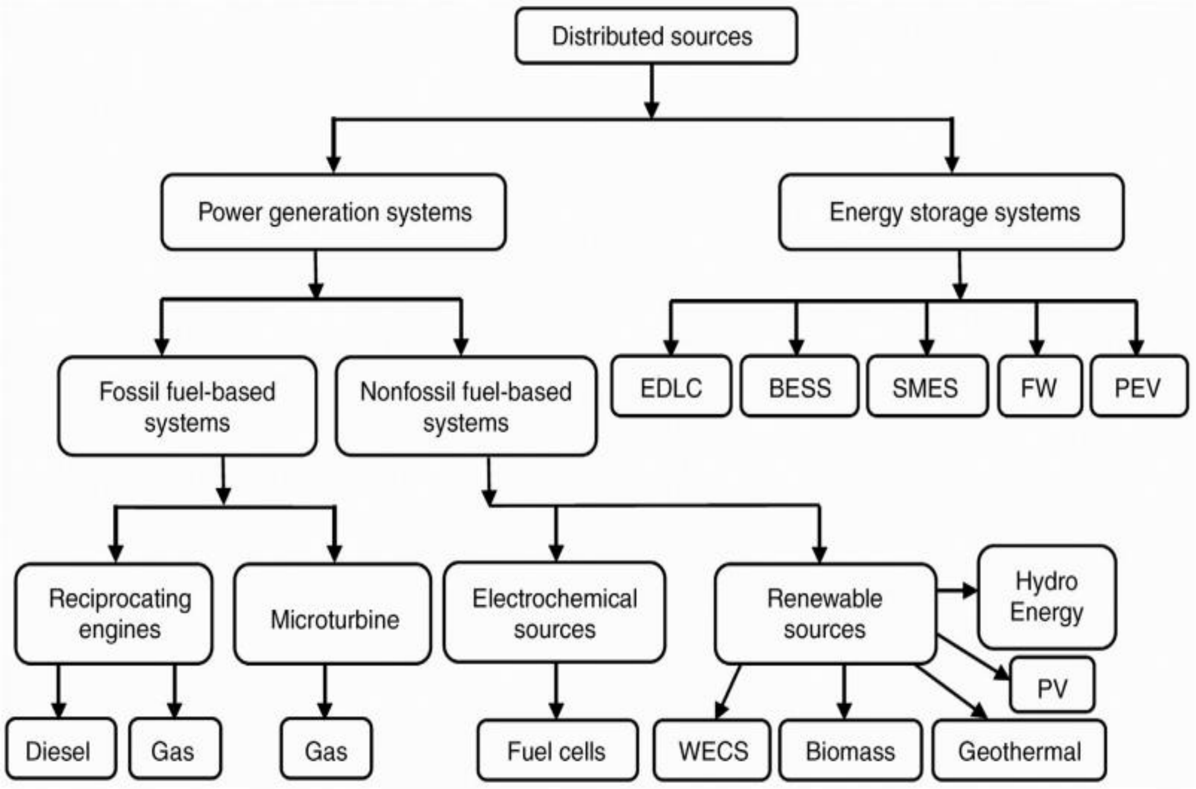


Figure 39 Different types of the DERs[31].

Both conventional generating systems (like diesel and gas generators) and nonconventional generation systems (like fuel cells and renewable energy sources) are capable of supplying electricity to the DG. Different types of energy storage system are also regarded as DG resources.

4.3 Renewable energy sources:

Fossil fuels are expected to account for 64% of the growth in energy over the next 20 years due to the problem of fossil fuel exhaustion and taking the greenhouse impact into consideration. By 2030, renewable energy sources, such as (wind, solar, hydro, wave, biofuels, etc.) will supply 18% of the world's energy[32]. Due to their absence of emissions, renewable energy sources will be an important part of the future smart grid system. In the following, Different forms of renewable energy are described.

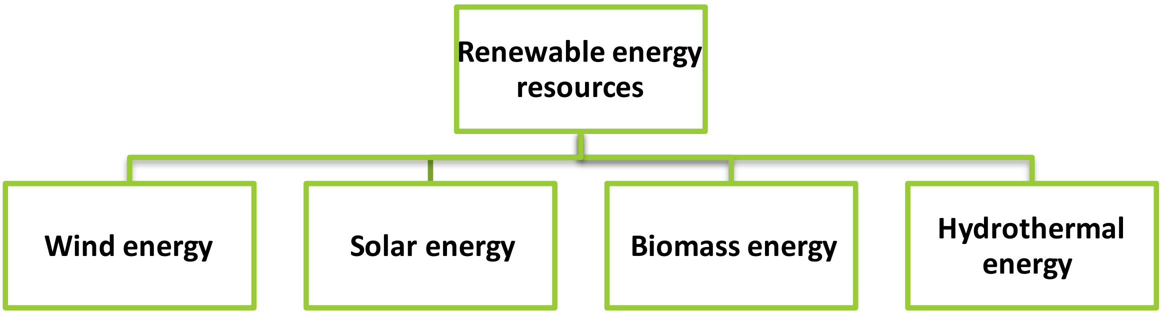


Figure 40 Renewable energy resources

4.4 Wind energy conversion system:

A wind energy conversion system (WECS) uses wind energy to generate mechanical energy, which it then transfers to an electrical generator to generate electricity. A wind turbine's generator can include a permanent magnet synchronous generator (PMSG), doubly fed induction generator, induction generator, synchronous generator, etc. The generator receives wind energy that was captured by the wind turbine. To achieve maximum power from the WECS, A pulse width modulation converter controls the generator's rotating speed. The output power of the generator is supplied to the grid through a generator-side converter and a grid-side inverter. A converter on the generator's side and an inverter on the grid's side work together to supply the generator's output power to the grid. A wind farm can be located on land, in the seashore, along the coastline, or in mountainous terrain. The WECS could be the most beneficial DG for the next smart grids. As a replacement for fossil fuels, wind energy is abundant, renewable, widely available, clean, affordable, emits no emissions while in use, and occupies a very little amount of land[33]. Environmental impacts are often less detrimental than those of other traditional power sources. Figure 41 shows the interconnection of a WECS.

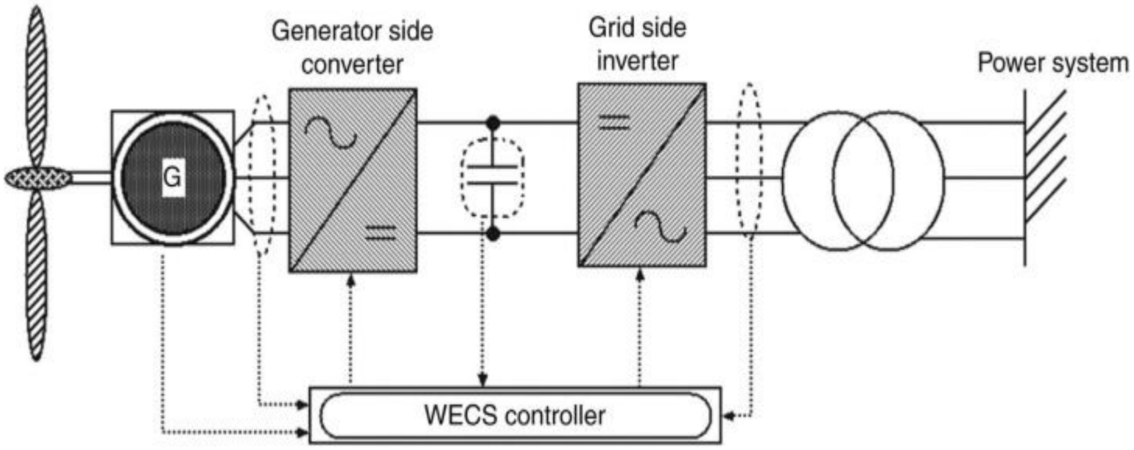


Figure 41 Wind energy conversion system[32].

The output power of the WECS changes due to the varying wind speed, which might result in a frequency variation in the power grid. There has already been a lot of study done to solve this issue.

4.4.1 Wind turbine generator types:

The most important component of a wind turbine is the wind turbine generator (WTG). It can be synchronous or asynchronous according to the requirements, however lately, asynchronous settings are used more often due to their advantages in maintaining synchronization within the grid. Wind turbine generators can have a variable or fixed speed. Based on it, the Western Electricity Coordinating Council (WECC) has identified four categories of WTG **Figure 42**

- Type 1: Fixed-Speed Wind Turbines.
- Type 2: Variable-Speed wind turbine with variable rotor resistance.
- Type 3: Variable-Speed wind turbine with a double fed inductive generator (DFIG).
- Type 4: Variable-Speed wind turbine with full converter.

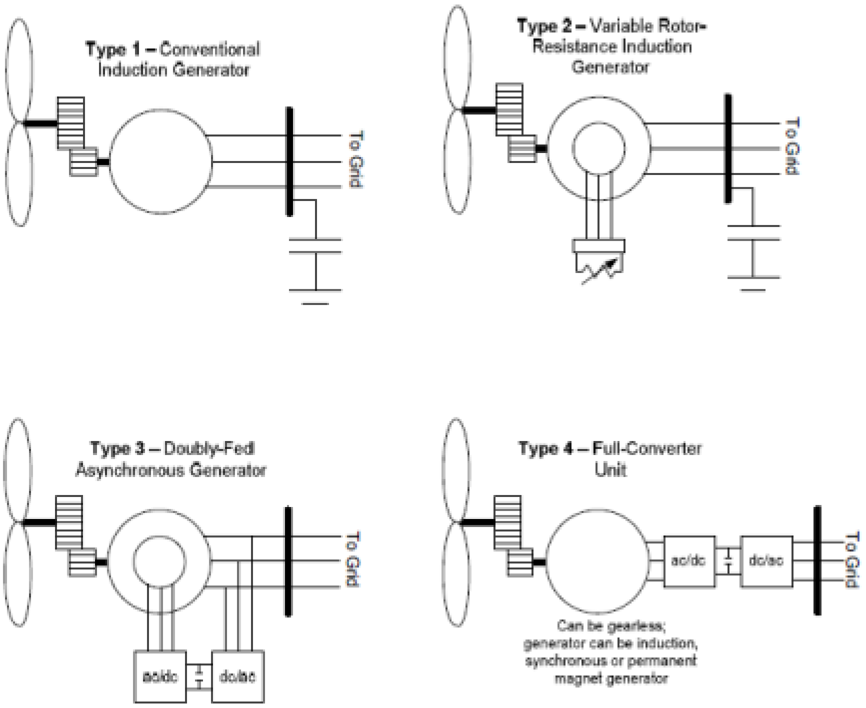


Figure 42 The four types of WTG.

4.5 PV energy system:

PV power systems convert sunlight directly into electricity. The PV system can be either grid-connected or stand-alone (off-grid). Like WECS, PV is another renewable energy source. However, the primary challenge to greater usage of PV systems is their high initial cost, but there have been ongoing price decreases. PV systems may be less expensive in some off-grid settings than the price of installing power lines on the property and the ensuing ongoing energy expenditures in distances of as little as a quarter mile. To meet any range of power requirements, from W to kW, and MW scale, PV modules may be arranged in an array of modules coupled in series and parallel. The PV array turns solar energy into electricity, and a DC-DC converter raises the output voltage to the required amount. In accordance with the needs of the PV system, a battery energy storage system (BESS) stores the power in the battery and transmits it to the PV system. The power grid receives power via a DC-AC converter. The PV energy generation system with the battery pack is shown in Figure 43

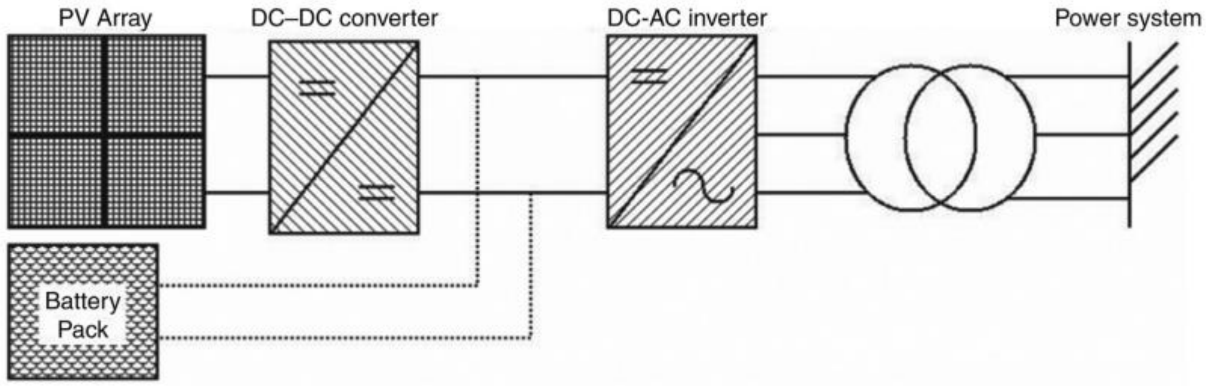


Figure 43 PV energy system.

4.5.1 Electronic inverter:

The inverter is utilized to convert the DC current output of the solar system or battery to the AC current. The basic operation of the DC to AC inverter is to create an AC signal from the DC signal, there are several types of the inverter used in the solar system.

4.5.1.1 Central inverter:

These inverters stand out for their enormous capacity of up to 4 MW. on-grid systems employ these types of inverters. To change the continuous voltage in the solar system into alternating voltage, one central inverter is utilized, to which all strings of solar panels are connected. In the case of large systems, a single central inverter is the most cost- and installation-effective option, however, there are certain disadvantages to using this kind of inverter, such as

- Compared to other types of inverters, it can be difficult to maintain.
- Since there is frequently only one central inverter, a central inverter malfunction makes the system out of service

Figure 44 Central inverter.

4.5.1.2 String inverter:

Most on-grid solar energy systems use this inverter because it is less expensive and easy to maintain than the central inverter. However, one drawback of utilizing this kind of inverter is that if one of the panels in the string is exposed to shadows, the amount of electricity produced by the string will drop; as a result, it must be verified that there are no shadow-causing factors[34].

Figure 45 String inverter.

4.5.1.3 Micro inverter:

These are connected to every solar panel individually and convert DC to AC on the roof, doing away with the need for an additional inverter. Because the panels are not linked to each other, they are not impacted by each other. This kind of inverter operates on on-grid systems, however, using many solar panels makes the system expensive, it is only utilized in small systems with a few panels[34].

Figure 46 Micro inverter.

4.6 Energy storage systems:

Systems for storage energy are a crucial component in the generation of renewable energy. Solar, wind, and hydroelectric power are all erratic sources of energy. Energy storage systems are deployed in the power generation system to provide the power grid with steady output power. Renewable energy sources (wind and solar) are also unstable; for example, wind energy might occasionally experience wind speeds that are insufficient to create electricity, and sunshine may only be available for 6–8 hours per day to generate electricity.

The energy storage systems can provide electricity to the users when the power generation is zero or the energy demand is high. Consequently, an energy storage system may be a crucial part of the smart grid (SG system) to increase the dependability of the power network. Energy storage comes in many different forms, including electric double-layer capacitors (EDLC), BESS, superconducting magnetic energy storage (SMES), flywheels (FW), plug-in electric vehicles (PEV), etc.

4.6.1 Electric double layer capacitor:

EDLC is sometimes referred to as a supercapacitor or ultracapacitor. The EDLC is an electrochemical capacitor that uses conducting polymers as its electrodes[35]. The EDLC only has a storage capacity of about 10 Wh/kg but can provide huge power effects per weight with an aim of up to 10 kW/kg. The storage time is brief, usually between 30 and 60 seconds. In the future, a 1-m3 EDLC storage might produce a 1–5 MW power pulse and weigh 100–500 kg[36]. The primary disadvantage of EDLCs is their expensive price.

4.6.2 Battery energy storage system:

An established technique for storing power is the battery. Because power and storage capacity are linked via the electrode surface, raising the power level also raises the storage capacity. Batteries come in a wide variety and are now widely used. In actuality, lead-acid battery development has been going on for more than 140 years. Despite this, a lot of work is being done to make lithium-ion (Li-ion), sodium-sulfur (NaS), and nickel-cadmium (Ni-Cd) batteries affordable alternatives for[37].

4.6.3 Superconducting magnetic energy storage:

The SMES system is a very new technological advancement. It works by storing energy in a magnetic field that is produced by a DC current flowing through a large superconducting coil that is kept at a low temperature. The product of the coil's self-inductance and the square of the current flowing through it yields the stored energy. There is a rapid reaction time. The primary disadvantage of SMES is their expensive price[38].

4.6.4 Flywheel:

The kinetic energy of a revolving disc, which is determined by the square of the rotational speed, determines the storage capacity in an FW. With the aid of an electric machine, a mass rotates at high speed on two magnetic bearings to reduce friction. When the machine functions as a motor (the FW accelerates), energy is delivered to the FW, charging the energy storage device. The electric machine regenerates through the drive (which slows the FW), discharging the FW energy storage system (FESS). FESSs have a big maximum output power, a long lifespan, and a high energy density. A FESS has an energy efficiency of up to 90%. The typical range of capacity is 3-133 kWh.

4.6.5 Plug in electric vehicle:

Recent PEVs have been significantly increased and typically come with a BESS.PEVs may contribute significantly to the grid's energy balancing efforts by acting as distributed energy storage sources, or "vehicle-to-grid" technology. A utility may be able to inject more power into the grid during key peak periods, preventing brownouts and rolling blackouts, by drawing on a sizable number of batteries linked into the SG throughout its service area. As a result, they can significantly contribute to raising the SG's power system dependability and power quality. When used in all-electric modes, PEVs may significantly reduce the need for oil and produce no air emissions. To charge their batteries, they do, however, rely on power plants, and those that use traditional fossil fuels pollute the environment. A PEV must be charged early in the morning when power demand is at its lowest and wind power is normally at its highest in order to operate it as cleanly as feasible. By engaging with the PEV to charge it at the most advantageous period, the SG technologies will assist in achieving this aim[39].

4.7 Problems and challenges:

Power generation, transmission, and distribution are the three primary components of the power system, and they are all typically controlled and managed individually. Due to advancements in network management technology, the power system has undergone modernization in order to provide users with both a high degree of ease and ubiquitous smart device control. This is required for the intelligent infrastructure, which is manageable by all smart platforms using a wide variety of applications. The traditional infrastructure of the existing network, however, has evolved into the primary issue in the network modernization process, posing some significant difficulties for power system engineers in the design and operation of the power grid. Distributed generations (DGs), on the other hand, will be a crucial component of the smart distribution network, and their implementation and integration on conventional networks will present some additional significant challenges that require more research and attention to prevent fundamental issues in the network with a smart structure[40].

Following is a quick explanation of some crucial difficulties regarding future networks with several DGs that must be addressed before being used in the smart grid.

4.7.1 Power losses:

Several DG units are anticipated to make up the future network. Long transmission lines will be required to provide electricity to the customers since specific DG units, like solar and wind farms, are far from load centers. The rise in losses that led to increased system expenses and power losses is directly correlated with increasing line length.

4.7.2 Power balancing:

Some DGs, like wind turbines and solar photovoltaic cells, have variable outputs all the time, which causes their power output to vary. A sophisticated system controller will be needed to handle these power variations from renewable energy sources, and it will also be difficult to achieve an energy balance between supply and demand. In order to address and fill these energy shortages, conventional generating and energy storage technologies will be required, making the provision of an enhanced power-balancing mechanism a fundamental problem for power systems.

4.7.3 High renewable energy penetration:

In smart grids, all network design plans are adjusted to take into account making the most of renewable energy sources while reducing reliance on traditional energy production. As a result, it is anticipated that RERs will play an important role in upcoming distribution networks. A predictable amount of energy is not guaranteed, however, because the production of RERs is directly dependent on climate change. This issue is resolved by incorporating several RERs into the grid, but doing so necessitates the development of new issues related to the technology's price, implementation, and other crucial components in the system.

Power system engineers are required to pay greater attention to certain very important problems with the fluctuation of power from RERs, as seen in Figure 47 [41].

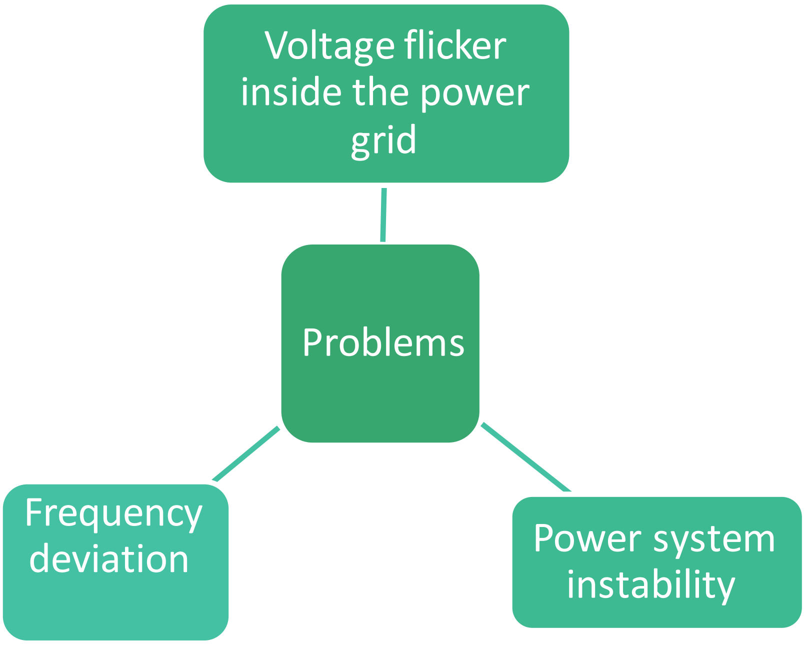


Figure 47 Problems with the fluctuation of power from RERs

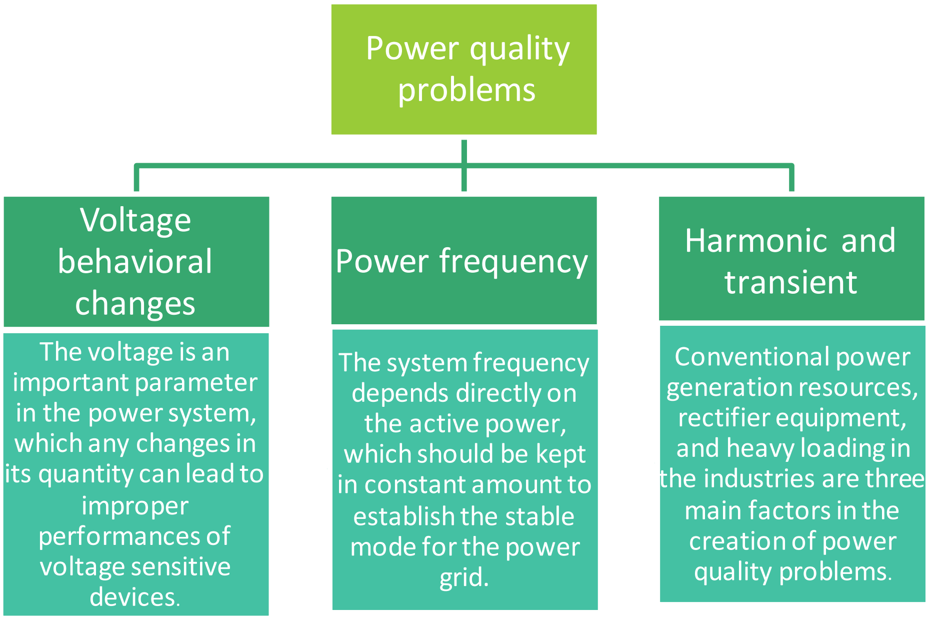
Research has been done to address the issues raised, and it shows that using energy storage systems can be a useful way to offset energy production that deviates from RERs. However, using them in the power grid increases overall system costs and necessitates the installation of large-scale energy storage systems, which can be very challenging in certain cases[42].

4.7.4 Impacts of real-time power market:

Independent power providers produce electricity in various instances. Due to the presence of this situation in the electrical market, claimant participants in the whole power sector compete for energy trades[43]. Electrical energy companies should efficiently use power plants that use fossil fuels in order to maximize profit and lower operating expenses. As a result, the optimal operation of DGs that are integrated with fossil fuel-based power units has become the primary concern for smart grid systems, and unit commitment schemes have been suggested as an appropriate technique to ascertain the optimal functioning of the smart power system [44], [45]. Correct power forecasting of the DGs units has become a significant difficulty for the real-time power market as a result of the variation in the output power of DGs units, which may raise the cost of electricity.

4.8 Stability and Power quality:

Stability is one of the most crucial elements that will often be required to maintain the system's performance. To maintain the power system in a stable condition, all of the control system mechanisms attempt to connect with each other. The creation of voltage and frequency stability, two classical states of stability, is essential for the power grid. Growing worries about the lack of energy supplies and the liberalization of the electrical market are the two primary factors that have contributed to an increase in the usage of RERs recently. Additionally, the transition to using smart houses with all electrical equipment to reap economic rewards led to an increase in electricity consumption, which led to greater usage of the power grid's capacity in emergency situations[46]. More power is exchanged on transmission lines as a result of increased energy usage, which may cause the power grid to operate close to its system stability constraints. Voltage collapse in the power system is more probable than ever under these circumstances[47]. System stability analysis will thus be required as a crucial component of network modernization in future smart grids. Power quality is another major issue. If the energy-producing resources' power output is of a standard quality, electrical equipment's lifespan will rise. Some power quality problems are described along with examples in



The voltage is an important parameter in the power system, which any changes in its quantity can lead to improper performances of voltage sensitive devices.

The system frequency depends directly on the active power, which should be kept in constant amount to establish the stable mode for the power grid.

Conventional power generation resources, rectifier equipment, and heavy loading in the industries are three main factors in the creation of power quality problems.

Figure 48 Power quality problems

4.9 Diagram of integration of PV systems in the network:

this section has a PV system integrated into the distribution system that has 7 bus as shown in Figure 49 is simulated using the ETAP software. The system is fed through a 13.8 kV grid, consists of 8 loads with a total power of 12.81 MVA. in addition, a PV system that has approx. 1 MW which consists of 6 PV arrays 170.7KW for each array, has been placed on bus 6 and bus7 to provide the required power for local loads and exchange the rest with the system

In this study, the capability and effectiveness of load flow assessment are investigated using simulation results obtained (total generation, load, demand, system losses, and critical load flow report). The results of Load Flow help maintain the proper operation of a Power System and also design and extend it.

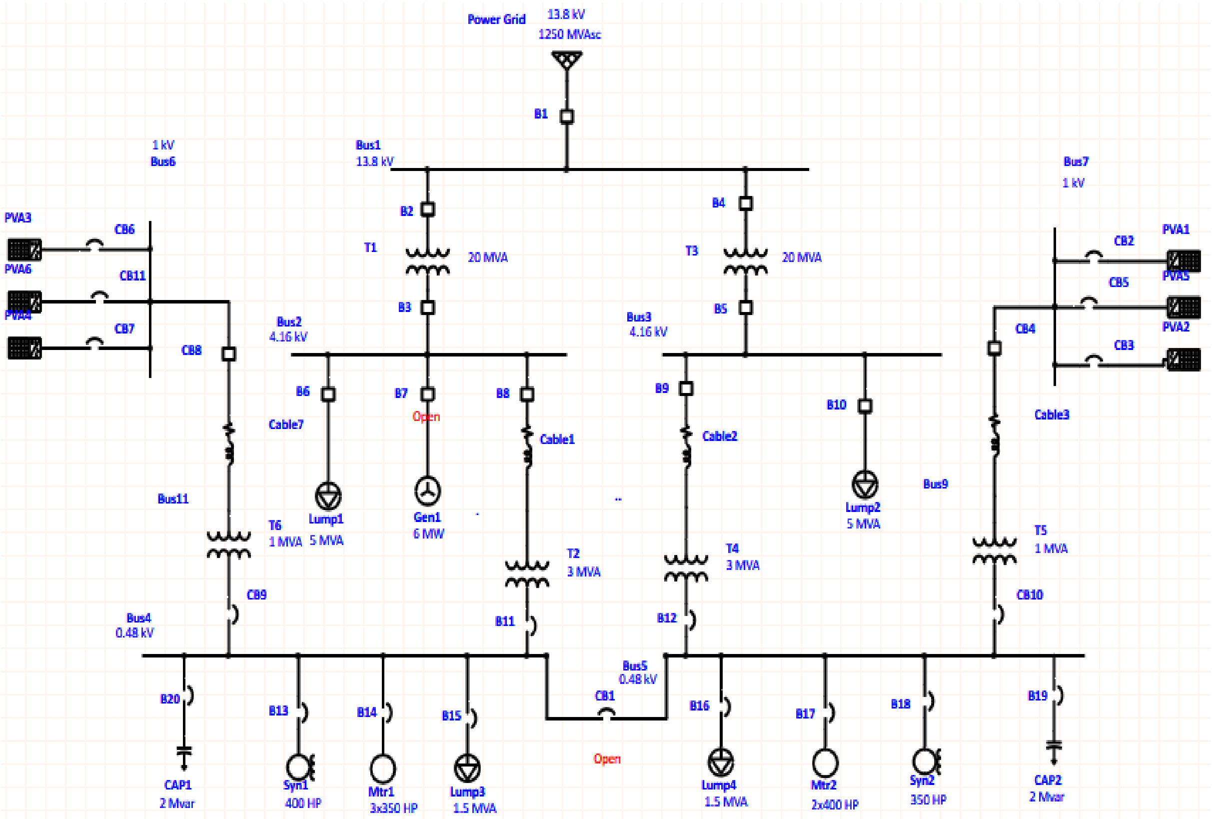
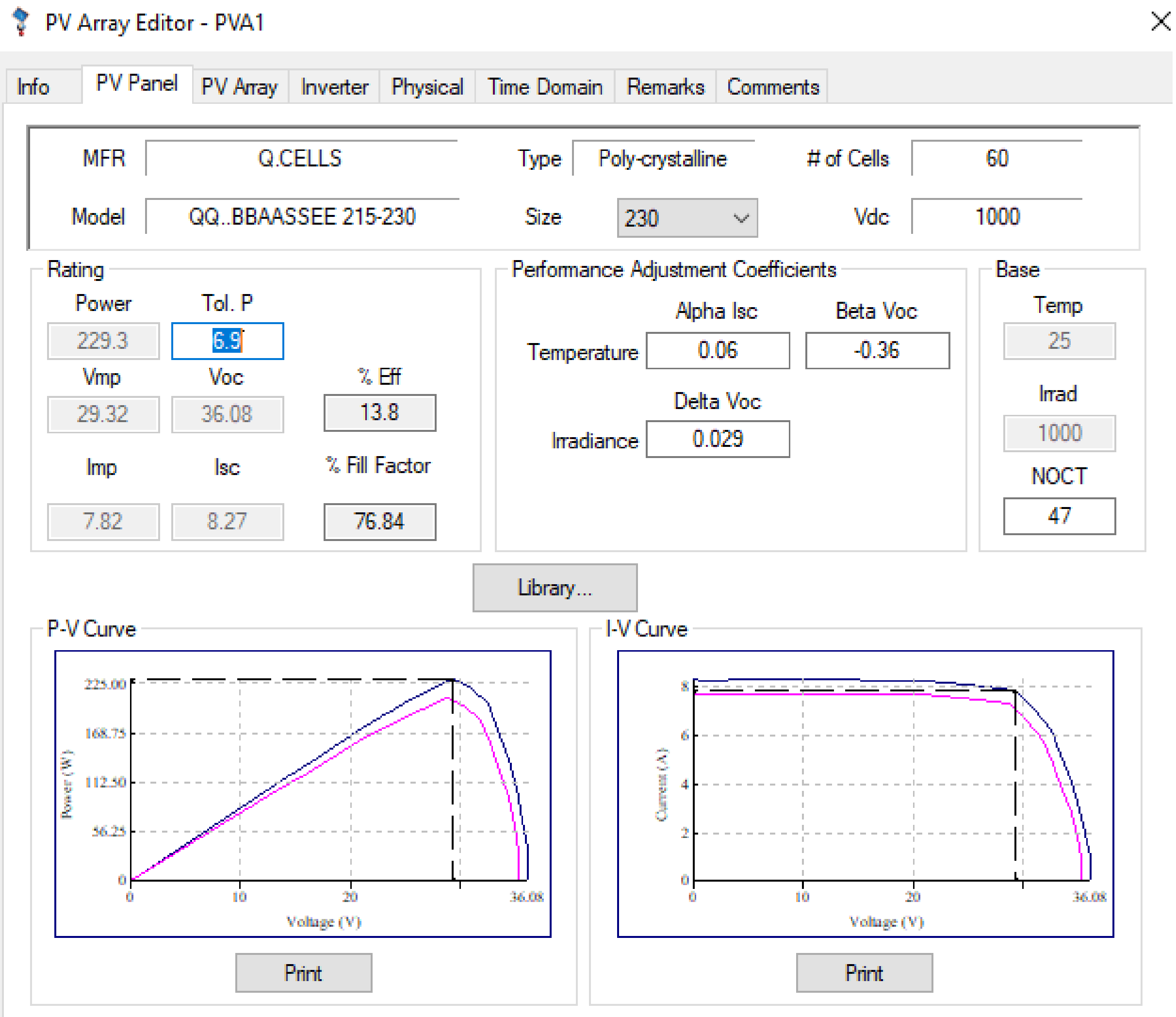


Figure 49 PV system integrated into the distribution system model.

4.9.1 PV Panel Page:

On this page, you can bring existing data from the library page. with the PV array producers that are available. And bring the data for simulation. photovoltaic characteristics including P-V and I-V curves are defined in the user-configurable ETAP Photovoltaic Library or specifying the maximum peak power voltage (Vmpp), maximum peak power current (Impp), open circuit voltage (Voc), and short circuit current (Isc). ETAP considers the effect of performance coefficients (α, β, γ) that define ranges in irradiance and cell temperature to automatically calculate the expected power output from the photovoltaic array



MFR: Q.CELLS
Type: Poly-crystalline
# of Cells: 60
Model: QQ..BBAASSEE 215-230
Size: 230
Vdc: 1000

Rating
Power: 229.3
Tol. P: 6.9
Vmp: 29.32
Voc: 36.08
% Eff: 13.8
Imp: 7.82
Isc: 8.27
% Fill Factor: 76.84

Performance Adjustment Coefficients
Temperature: Alpha Isc 0.06, Beta Voc -0.36
Irradiance: Delta Voc 0.029

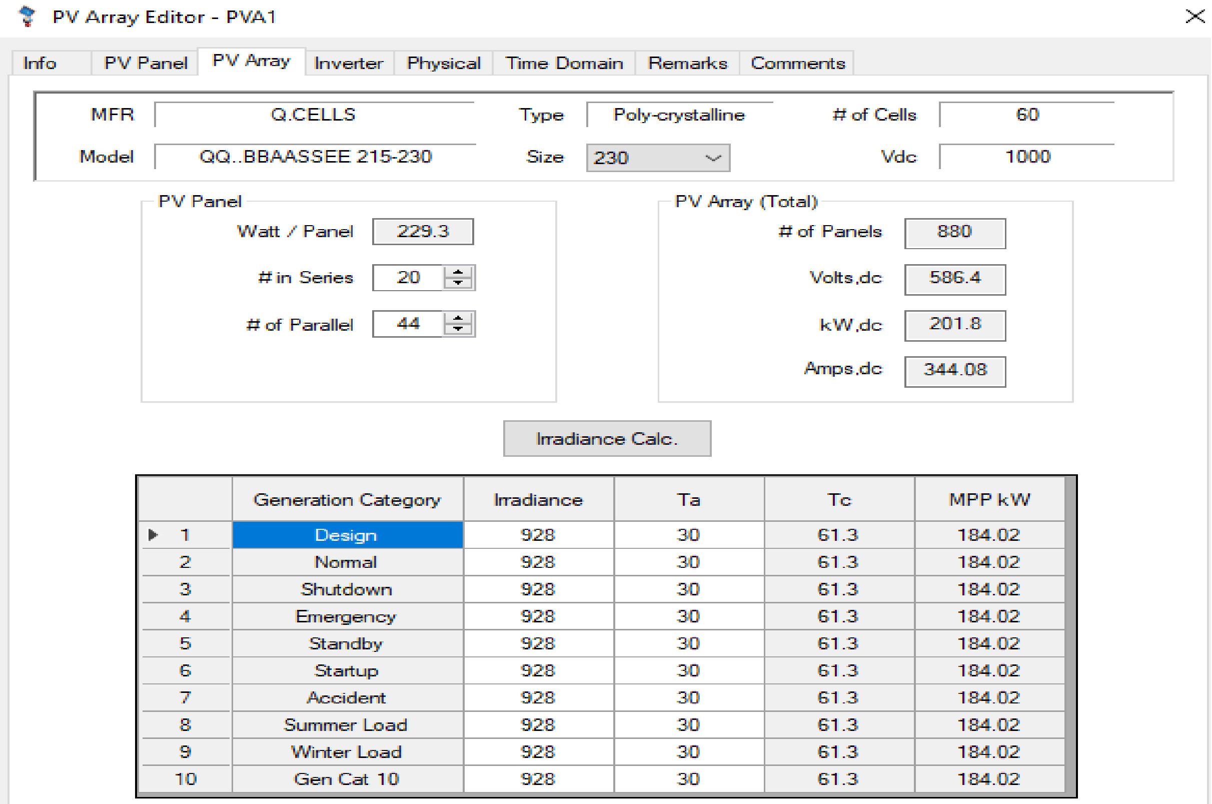
Base
Temp: 25
Irrad: 1000
NOCT: 47

4.9.2 PV Array Page:

On this page, this allows the user to enter the number of PV panels connected in series and parallel. and shows the calculated total number of panels:

- The total DC voltage in Volts calculated based on the number of panels in series.
- The total DC current in Amps calculated based on the number of panels in parallel.
- The total DC power in kW calculated based on the number of panels in series and parallel that make up the PV array.

The user can input the outside temperature Ta in degrees Celsius. The cell temperature Tc is recalculated as the irradiance and ambient temperature Ta vary. the efficiency and power output from the panel is lower the higher the Tc.



MFR: Q.CELLS
Type: Poly-crystalline
# of Cells: 60
Model: QQ..BBAASSEE 215-230
Size: 230
Vdc: 1000

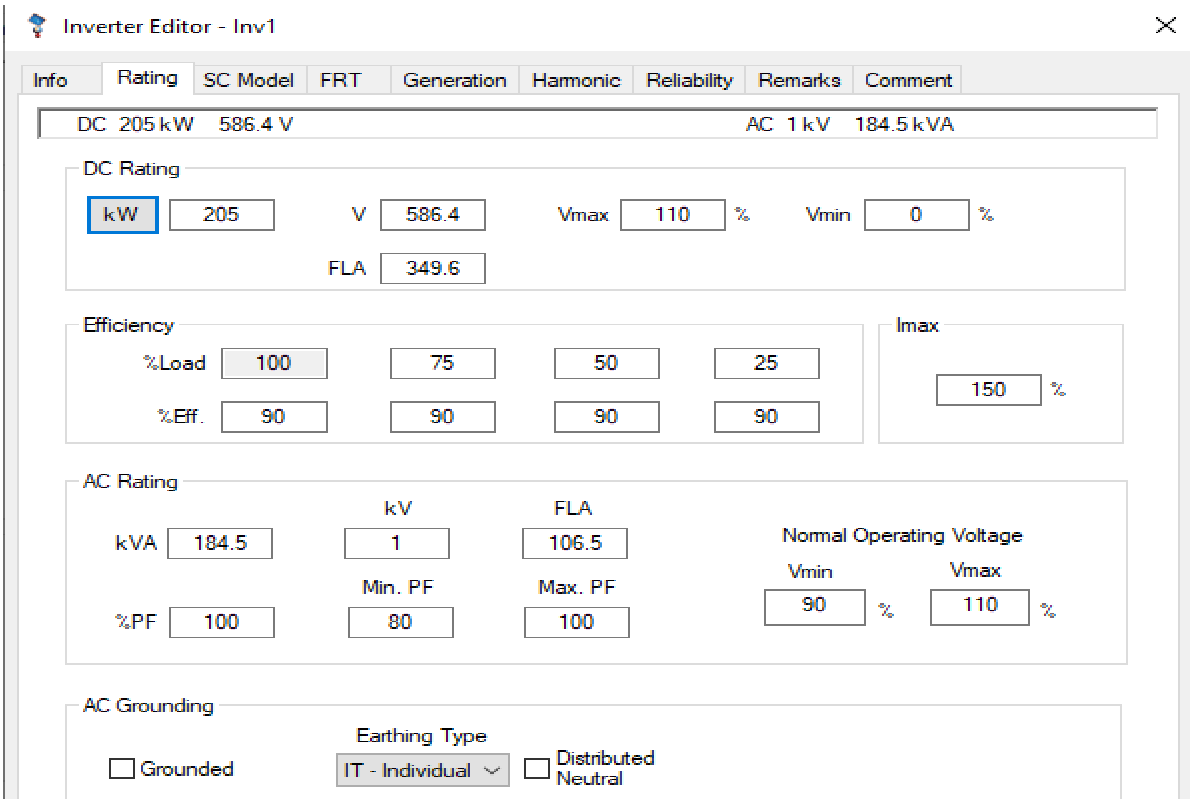
PV Panel
Watt / Panel: 229.3
in Series: 20
of Parallel: 44

PV Array (Total)
# of Panels: 880
Volts,dc: 586.4
kW,dc: 201.8
Amps,dc: 344.08

	Generation Category	Irradiance	Ta	Tc	MPP kW
▶ 1	Design	928	30	61.3	184.02
2	Normal	928	30	61.3	184.02
3	Shutdown	928	30	61.3	184.02
4	Emergency	928	30	61.3	184.02
5	Standby	928	30	61.3	184.02
6	Startup	928	30	61.3	184.02
7	Accident	928	30	61.3	184.02
8	Summer Load	928	30	61.3	184.02
9	Winter Load	928	30	61.3	184.02
10	Gen Cat 10	928	30	61.3	184.02

4.9.3 Rating page - Inverter Editor:

On this page, can be modified the inverter ratings, the short-circuit current to an AC system failure, and the AC grounding parameter. And entering DC Rating settings (kW, FLA, Vmax, Vmin) and AC Rating settings (kVA, kV, FLA, %PF, K).



DC 205 kW 586.4 V AC 1 kV 184.5 kVA

DC Rating
kW: 205
V: 586.4
Vmax: 110 %
Vmin: 0 %
FLA: 349.6

Efficiency

%Load	100	75	50	25
%Eff.	90	90	90	90

Imax: 150 %

AC Rating
kVA: 184.5
kV: 1
FLA: 106.5
%PF: 100
Min. PF: 80
Max. PF: 100

Normal Operating Voltage
Vmin: 90 %
Vmax: 110 %

AC Grounding
☐ Grounded
Earthing Type: IT - Individual
☐ Distributed Neutral

4.9.4 Simulation power flow analysis of integration of PV systems in the network:

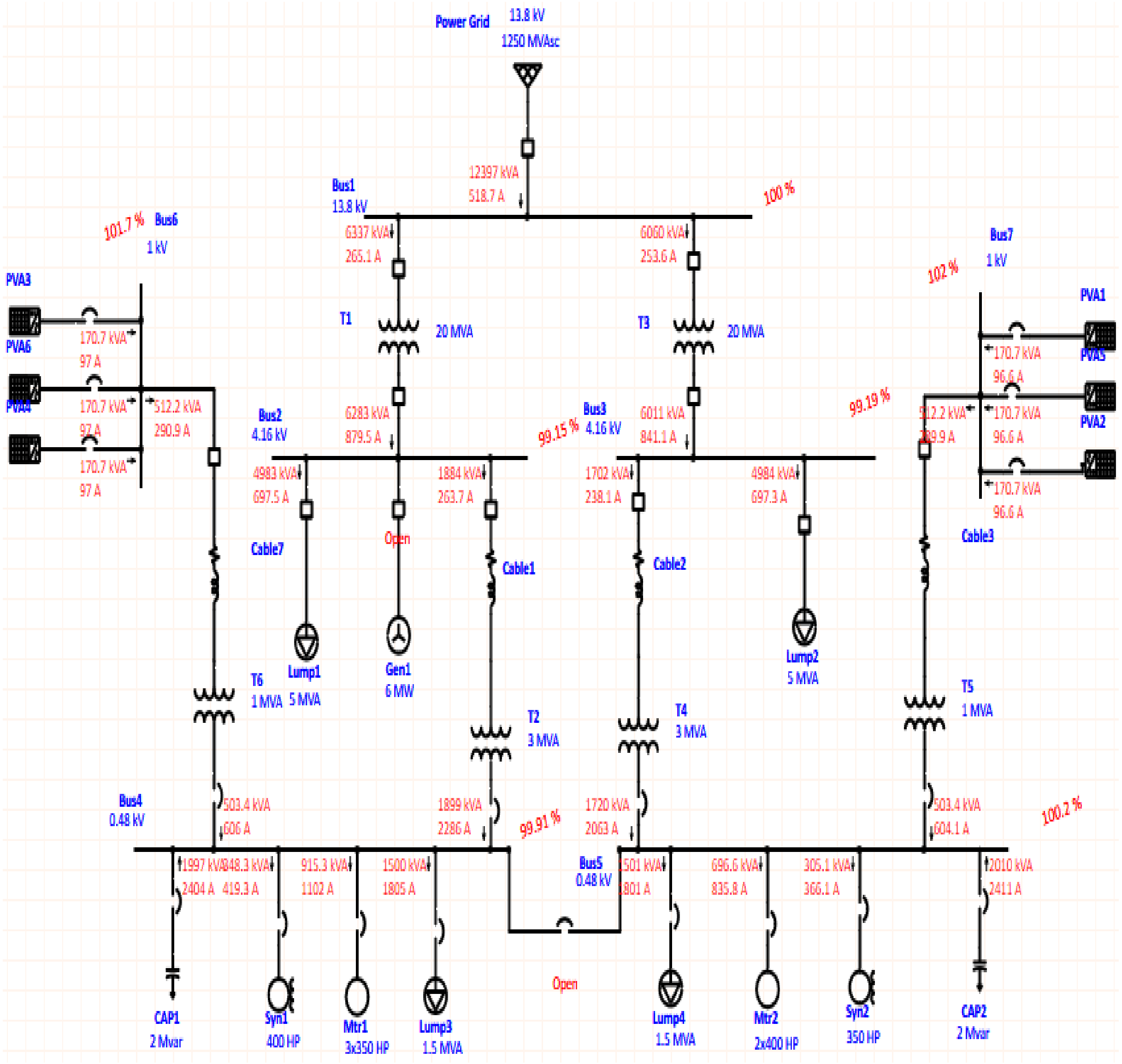
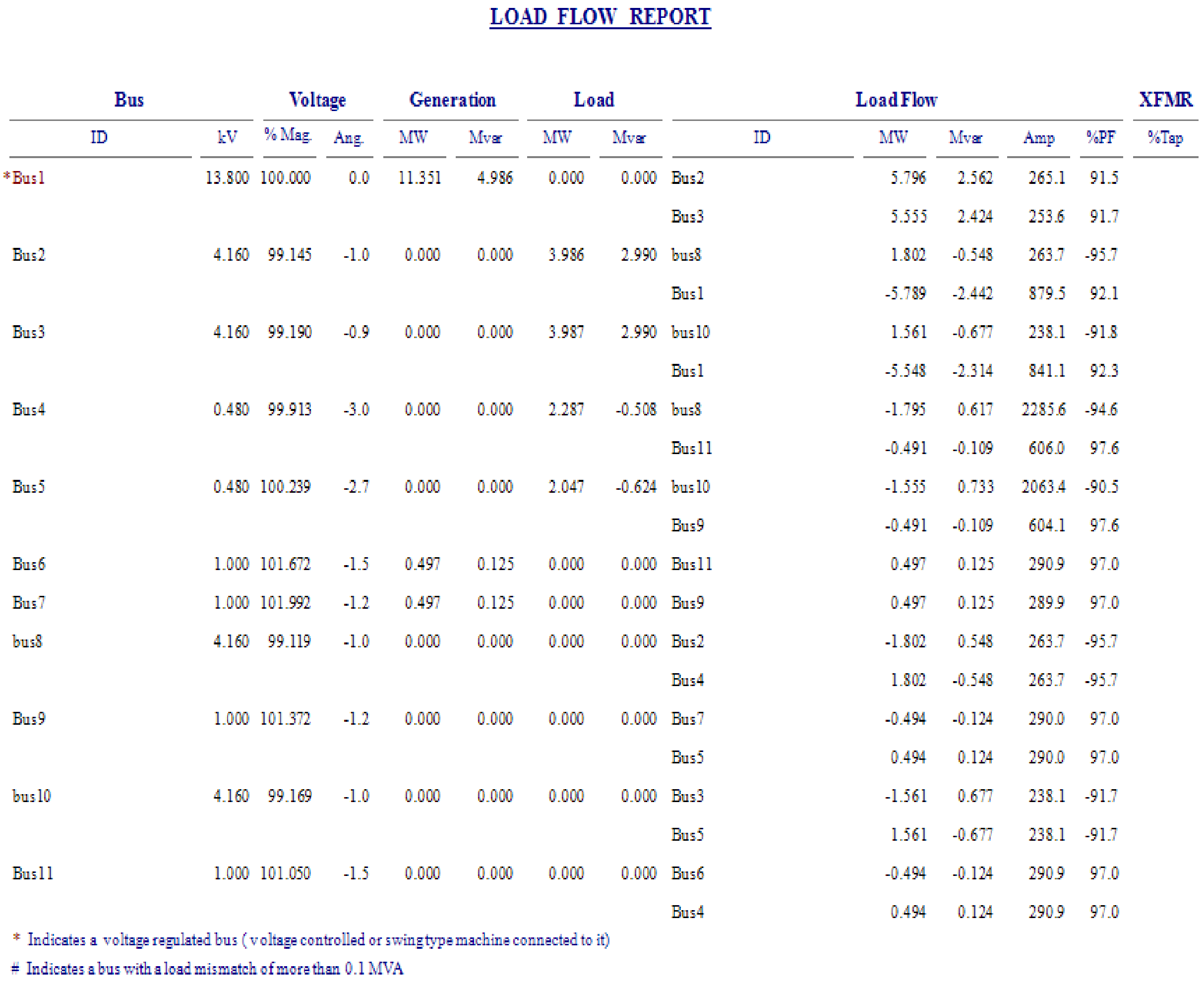


Figure 50 Power flow analysis of integration of PV systems

4.9.4.1 Load flow report:



LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
*Bus1	13.800	100.000	0.0	11.351	4.986	0.000	0.000	Bus2	5.796	2.562	265.1	91.5	
								Bus3	5.555	2.424	253.6	91.7	
Bus2	4.160	99.145	-1.0	0.000	0.000	3.986	2.990	bus8	1.802	-0.548	263.7	-95.7	
								Bus1	-5.789	-2.442	879.5	92.1	
Bus3	4.160	99.190	-0.9	0.000	0.000	3.987	2.990	bus10	1.561	-0.677	238.1	-91.8	
								Bus1	-5.548	-2.314	841.1	92.3	
Bus4	0.480	99.913	-3.0	0.000	0.000	2.287	-0.508	bus8	-1.795	0.617	2285.6	-94.6	
								Bus11	-0.491	-0.109	606.0	97.6	
Bus5	0.480	100.239	-2.7	0.000	0.000	2.047	-0.624	bus10	-1.555	0.733	2063.4	-90.5	
								Bus9	-0.491	-0.109	604.1	97.6	
Bus6	1.000	101.672	-1.5	0.497	0.125	0.000	0.000	Bus11	0.497	0.125	290.9	97.0	
Bus7	1.000	101.992	-1.2	0.497	0.125	0.000	0.000	Bus9	0.497	0.125	289.9	97.0	
bus8	4.160	99.119	-1.0	0.000	0.000	0.000	0.000	Bus2	-1.802	0.548	263.7	-95.7	
								Bus4	1.802	-0.548	263.7	-95.7	
Bus9	1.000	101.372	-1.2	0.000	0.000	0.000	0.000	Bus7	-0.494	-0.124	290.0	97.0	
								Bus5	0.494	0.124	290.0	97.0	
bus10	4.160	99.169	-1.0	0.000	0.000	0.000	0.000	Bus3	-1.561	0.677	238.1	-91.7	
								Bus5	1.561	-0.677	238.1	-91.7	
Bus11	1.000	101.050	-1.5	0.000	0.000	0.000	0.000	Bus6	-0.494	-0.124	290.9	97.0	
								Bus4	0.494	0.124	290.9	97.0	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

# Indicates a bus with a load mismatch of more than 0.1 MVA

This table shows the results of the power flow. by taking the example on bus6 and bus7 he indicates voltage regulation (controlled voltage), its voltage is 1 KV, his power in MW is 0.497 and in MVAR is 0.125, load flow is 0.497 MW, current is 290.9 A, power factor 97%, For the other buses, each differs in its own results.

4.9.5 Simulation of short circuit Analysis of integration of PV systems in the network:

The main goals of short circuit current calculations are to: provide the distribution system with adequate overcurrent protection equipment that will protect workers from injury, reduce component damage, reduce the extent and duration of maintenance interruptions in the event of equipment failures; and check the facilities of the power distribution system circuit breakers, bus bars to see if they can withstand short-circuit current. IEC standard is selected to calculate short circuit current. IEC standard is selected to calculate short circuit current. by analysis 3 phase fault on bus 7 as shown in Figure 51

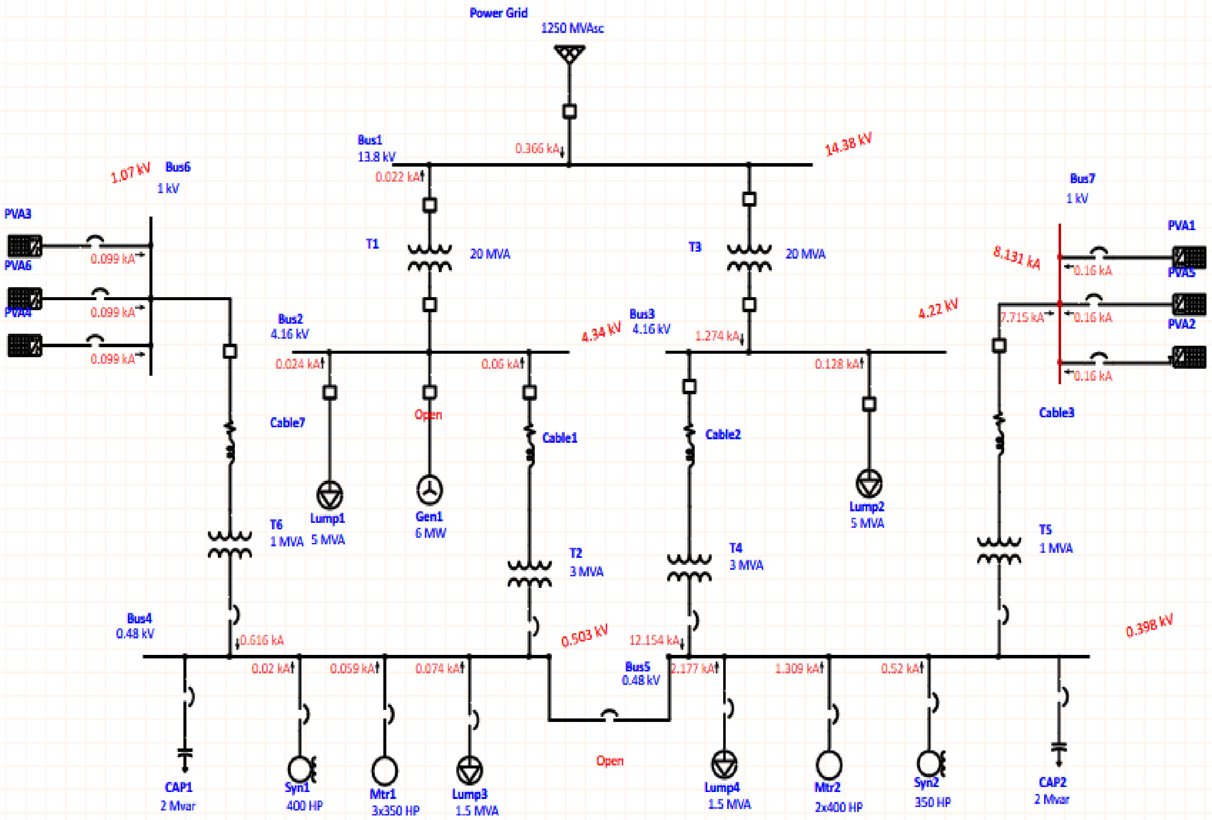


Figure 51 Short Circuit Analysis 3 phase device duty IEC on bus 7.

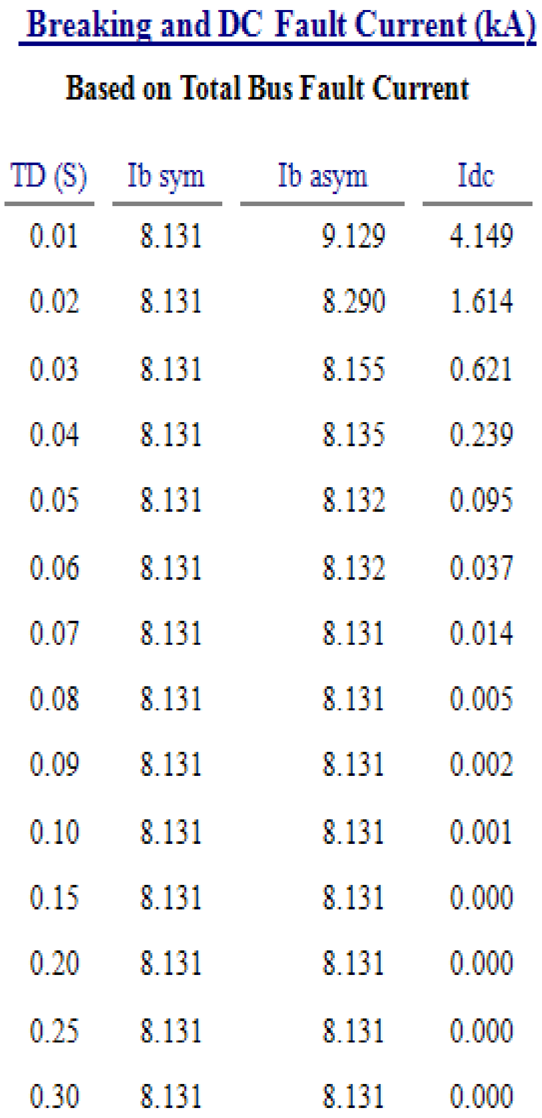
4.9.5.1 Short circuit report :

SHORT-CIRCUIT REPORT

3-Phase fault at bus: **Bus7**

Nominal kV = 1.000
Voltage c Factor = 1.05 (User-Defined)
Peak Value = 15.926 kA Method C
Steady State = 7.664 kA rms

Contribution		Voltage & Initial Symmetrical Current (rms)				
From Bus ID	To Bus ID	% V From Bus	kA Real	kA Imaginary	X/R Ratio	kA Magnitude
Bus7	Total	0.00	2.681	-7.677	2.9	8.131
Bus9	Bus7	16.52	2.323	-7.357	3.2	7.715
PVA1	Bus7	0.00	0.119	-0.107	0.9	0.160
PVA2	Bus7	0.00	0.119	-0.107	0.9	0.160
PVA5	Bus7	0.00	0.119	-0.107	0.9	0.160
Bus5	Bus9	83.01	2.323	-7.357	3.2	7.715
PVA3	Bus6	106.51	0.096	-0.021	0.2	0.099
PVA4	Bus6	106.51	0.096	-0.021	0.2	0.099
PVA6	Bus6	106.51	0.096	-0.021	0.2	0.099



Breaking and DC Fault Current (kA)

Based on Total Bus Fault Current

TD (S)	Ib sym	Ib asym	Idc
0.01	8.131	9.129	4.149
0.02	8.131	8.290	1.614
0.03	8.131	8.155	0.621
0.04	8.131	8.135	0.239
0.05	8.131	8.132	0.095
0.06	8.131	8.132	0.037
0.07	8.131	8.131	0.014
0.08	8.131	8.131	0.005
0.09	8.131	8.131	0.002
0.10	8.131	8.131	0.001
0.15	8.131	8.131	0.000
0.20	8.131	8.131	0.000
0.25	8.131	8.131	0.000
0.30	8.131	8.131	0.000

In the event of an outage or fault, the coupling circuit breaker is open B21 and the other source provides all the power until maintenance of bus 7.

4.10 Diagram of integration of wind turbine generator in the network:

this section has a wind turbine generator (WGT) integrated into the distribution system that has 6 bus as shown in figure 50 is simulated using the ETAP software. The system is fed through a 13.8 kV grid, consists of 8 loads with a total power of 12.81 MVA. in addition, wind turbine generator that has 1 MW, has been placed on bus 6 to provide the required power for local loads and exchange the rest with the system

In this study, the capability and effectiveness of load flow assessment are investigated using simulation results obtained (total generation, load, demand, system losses, and critical load flow report). The results of Load Flow help maintain the proper operation of a Power System and also design and extend it.

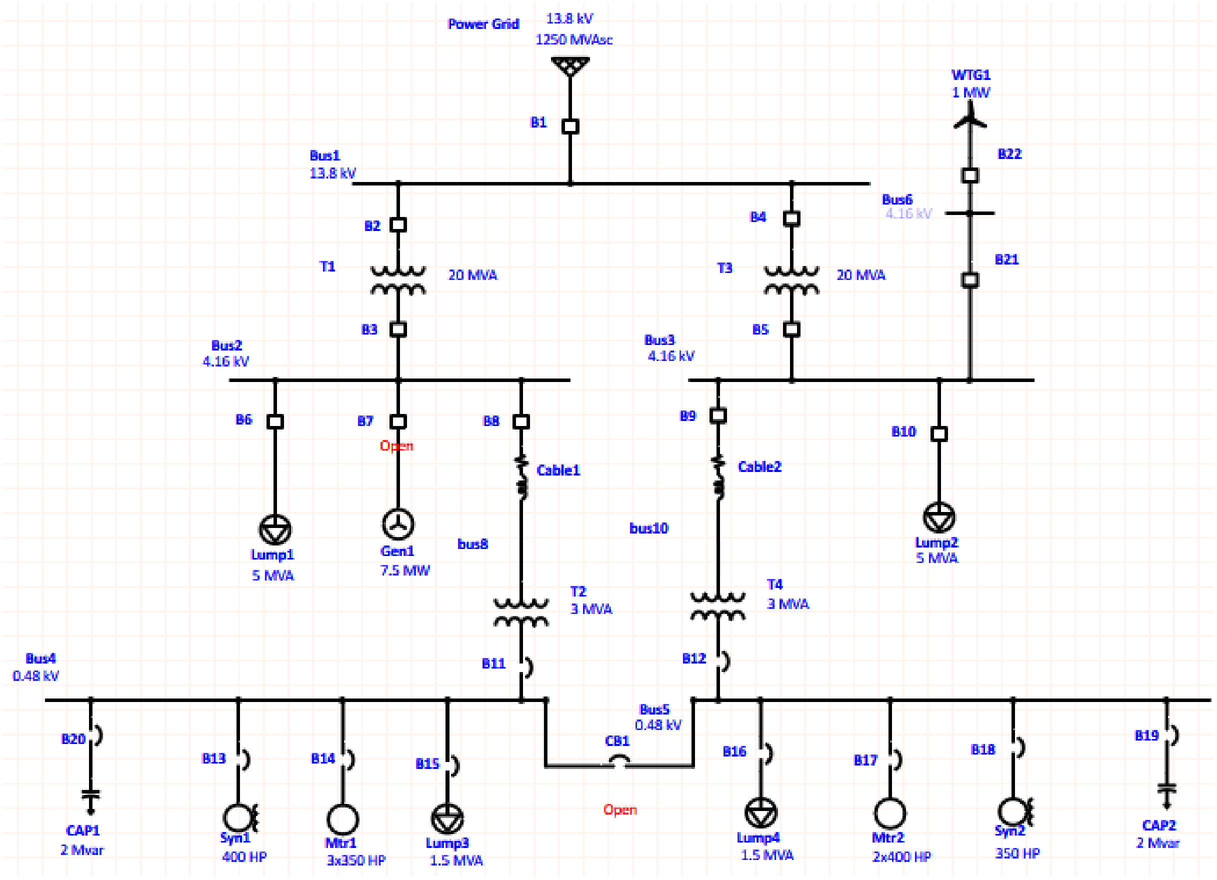


Figure 52 WGT integrated into the distribution system model.

4.11 Power flow analysis:

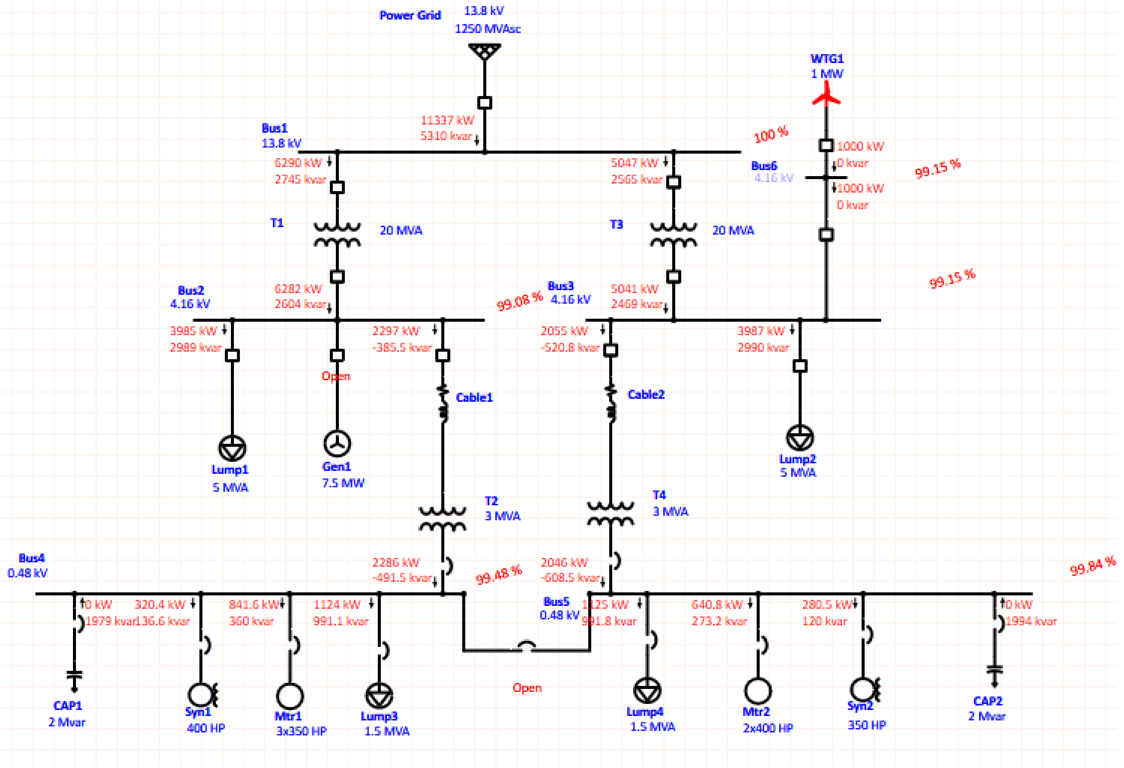
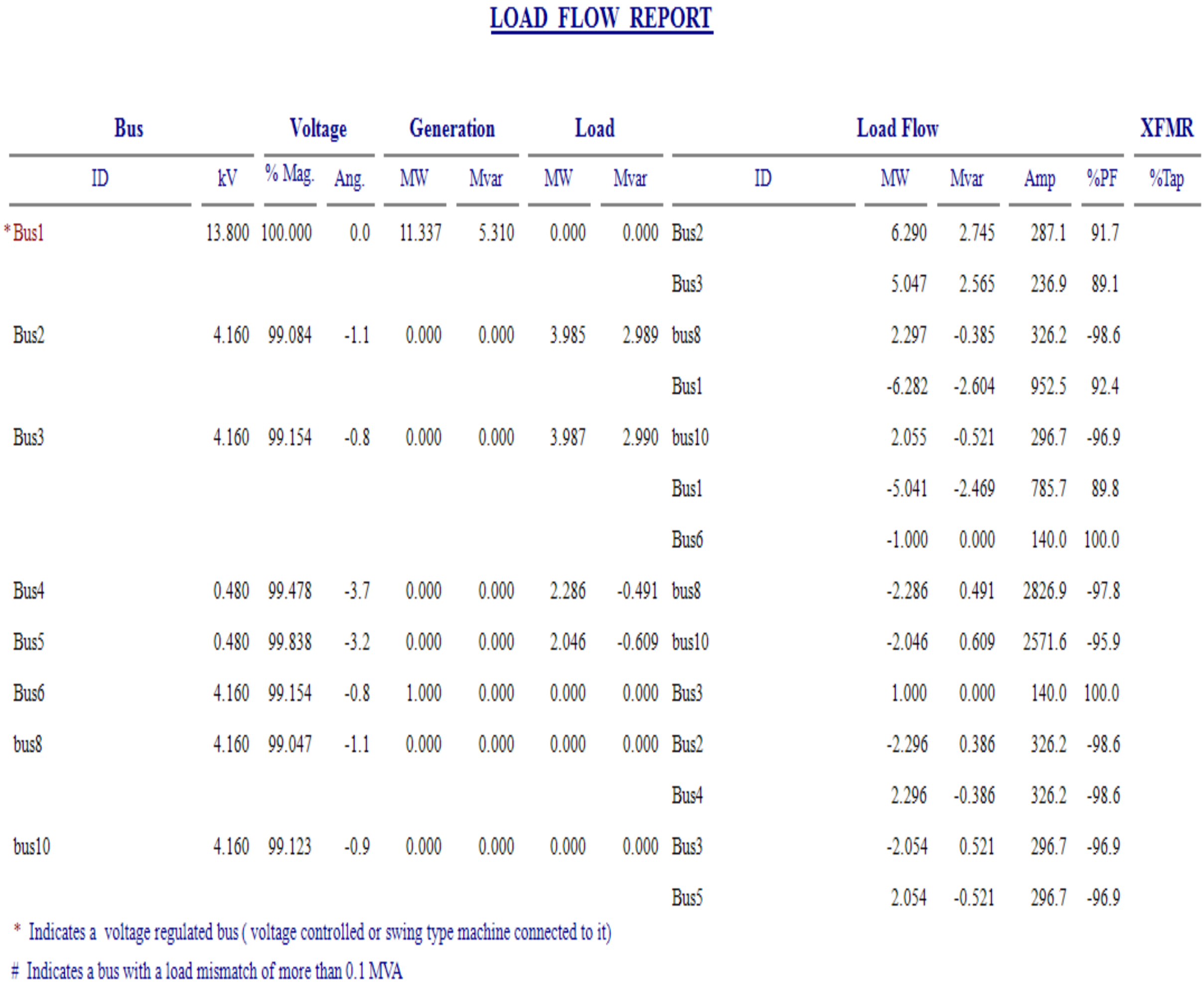


Figure 53 Power flow analysis

4.11.1 Power flow report:



LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
*Bus1	13.800	100.000	0.0	11.337	5.310	0.000	0.000	Bus2	6.290	2.745	287.1	91.7	
								Bus3	5.047	2.565	236.9	89.1	
Bus2	4.160	99.084	-1.1	0.000	0.000	3.985	2.989	bus8	2.297	-0.385	326.2	-98.6	
								Bus1	-6.282	-2.604	952.5	92.4	
Bus3	4.160	99.154	-0.8	0.000	0.000	3.987	2.990	bus10	2.055	-0.521	296.7	-96.9	
								Bus1	-5.041	-2.469	785.7	89.8	
								Bus6	-1.000	0.000	140.0	100.0	
Bus4	0.480	99.478	-3.7	0.000	0.000	2.286	-0.491	bus8	-2.286	0.491	2826.9	-97.8	
Bus5	0.480	99.838	-3.2	0.000	0.000	2.046	-0.609	bus10	-2.046	0.609	2571.6	-95.9	
Bus6	4.160	99.154	-0.8	1.000	0.000	0.000	0.000	Bus3	1.000	0.000	140.0	100.0	
bus8	4.160	99.047	-1.1	0.000	0.000	0.000	0.000	Bus2	-2.296	0.386	326.2	-98.6	
								Bus4	2.296	-0.386	326.2	-98.6	
bus10	4.160	99.123	-0.9	0.000	0.000	0.000	0.000	Bus3	-2.054	0.521	296.7	-96.9	
								Bus5	2.054	-0.521	296.7	-96.9	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

\# Indicates a bus with a load mismatch of more than 0.1 MVA

4.12 Transient stability analysis:

4.12.1 Case:1

The transient stability is analysed for 6 bus system which is shown in Figure 50, The three-phase fault is created at bus 2 for 1.00 seconds and is cleared after 1.20 seconds with the help of transient stability study case editor.

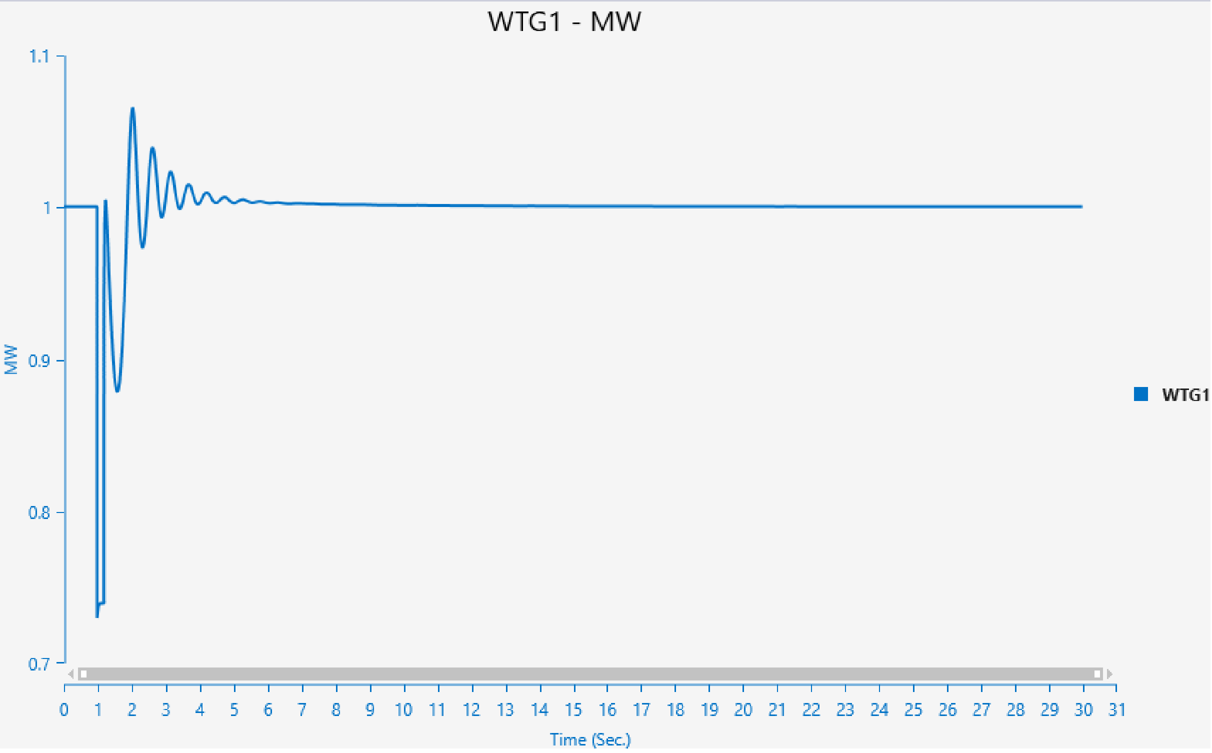


Figure 54 WGT Active power (MW)

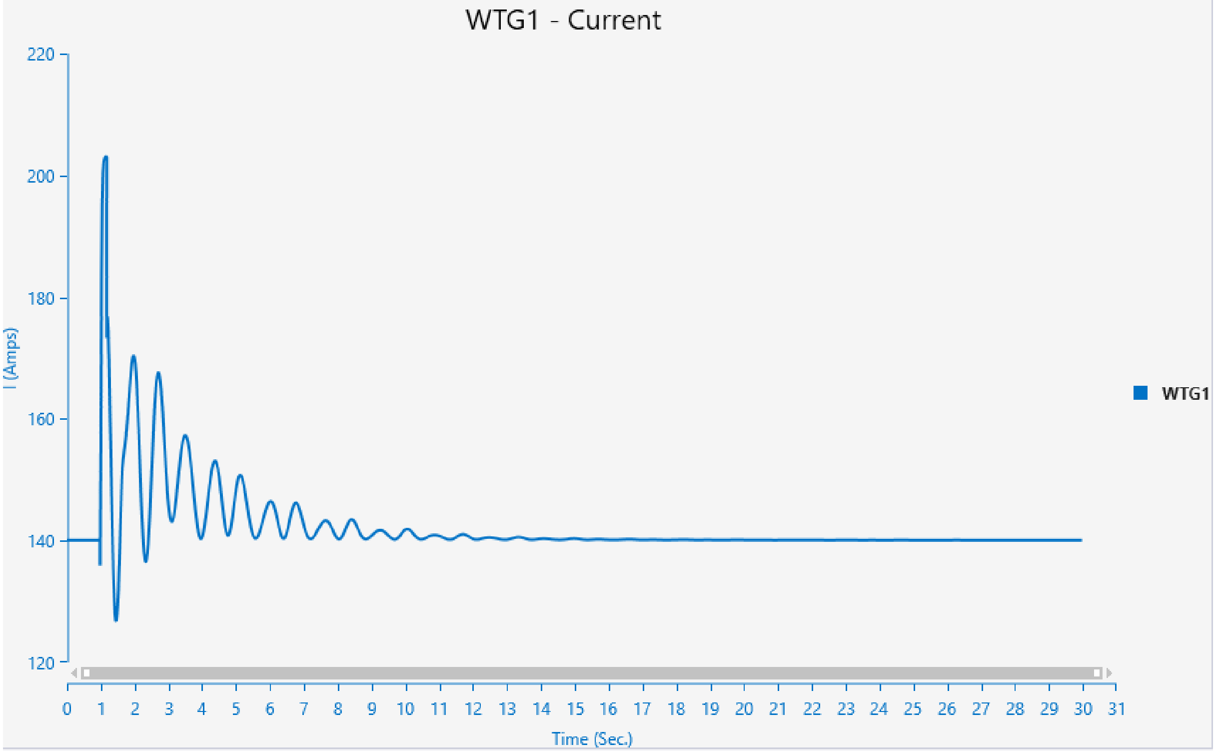


Figure 55 WTG-Current

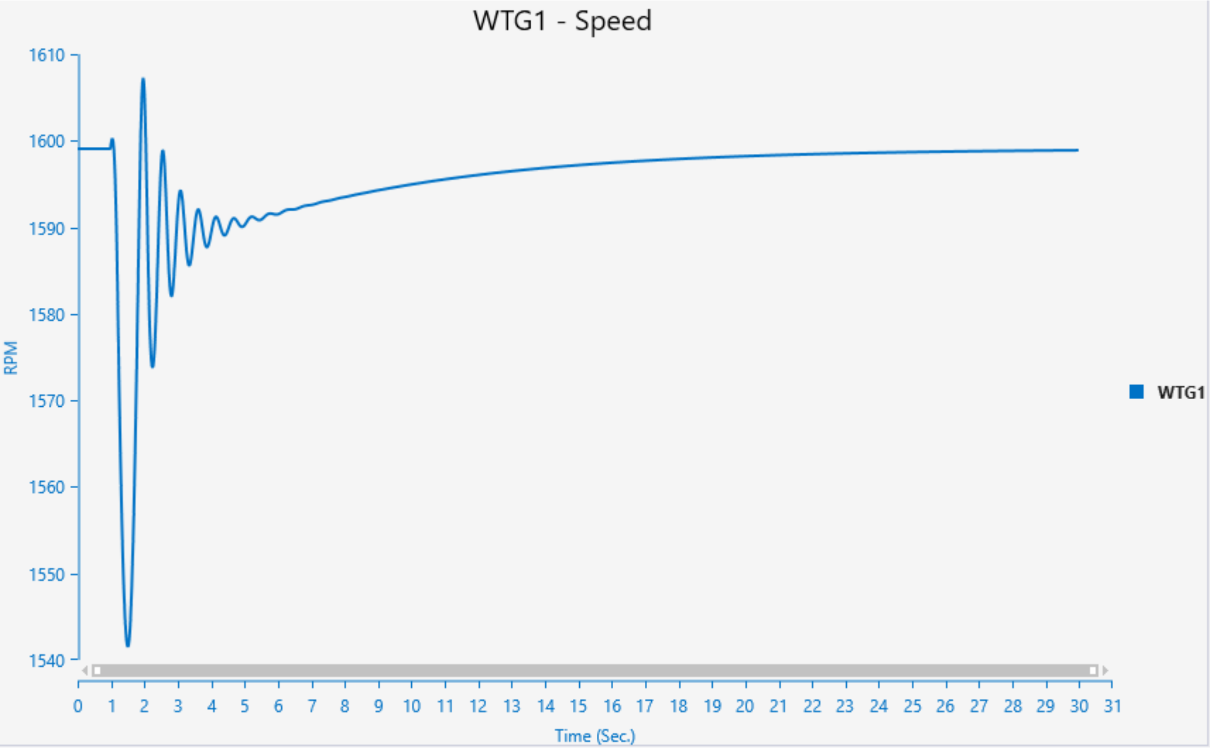


Figure 56 WTG-Speed

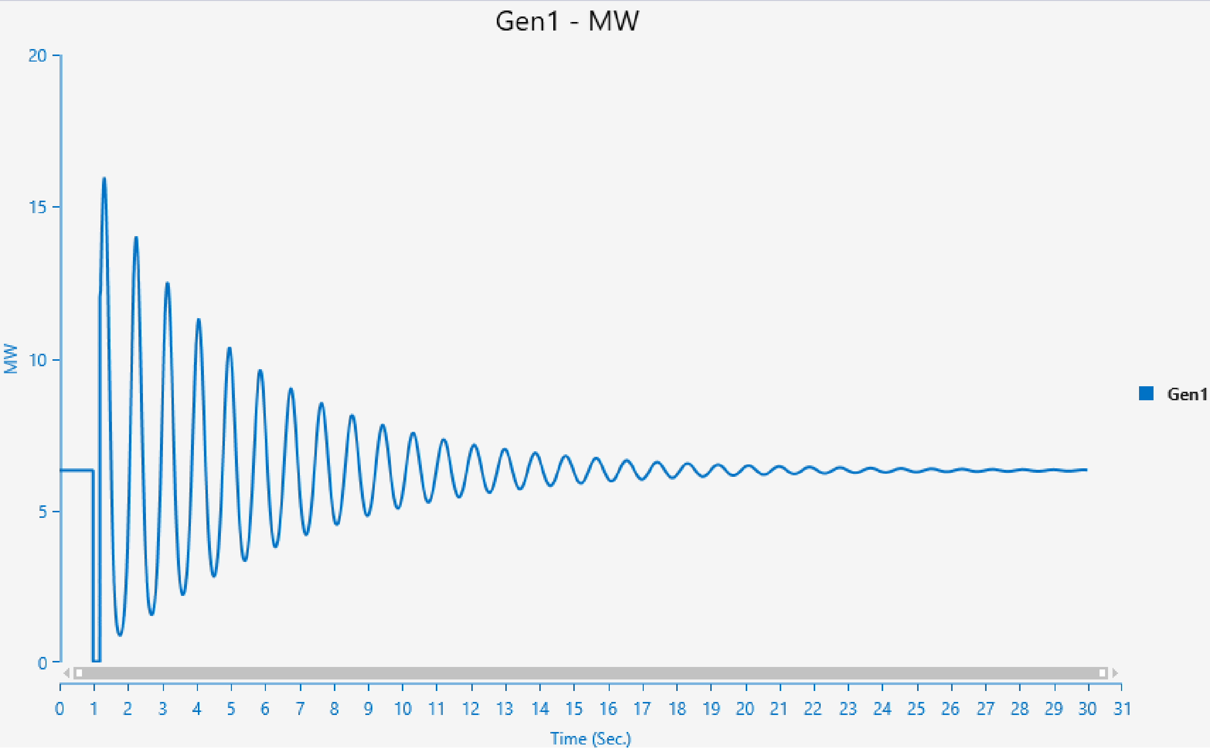


Figure 57 Generator Electrical Power

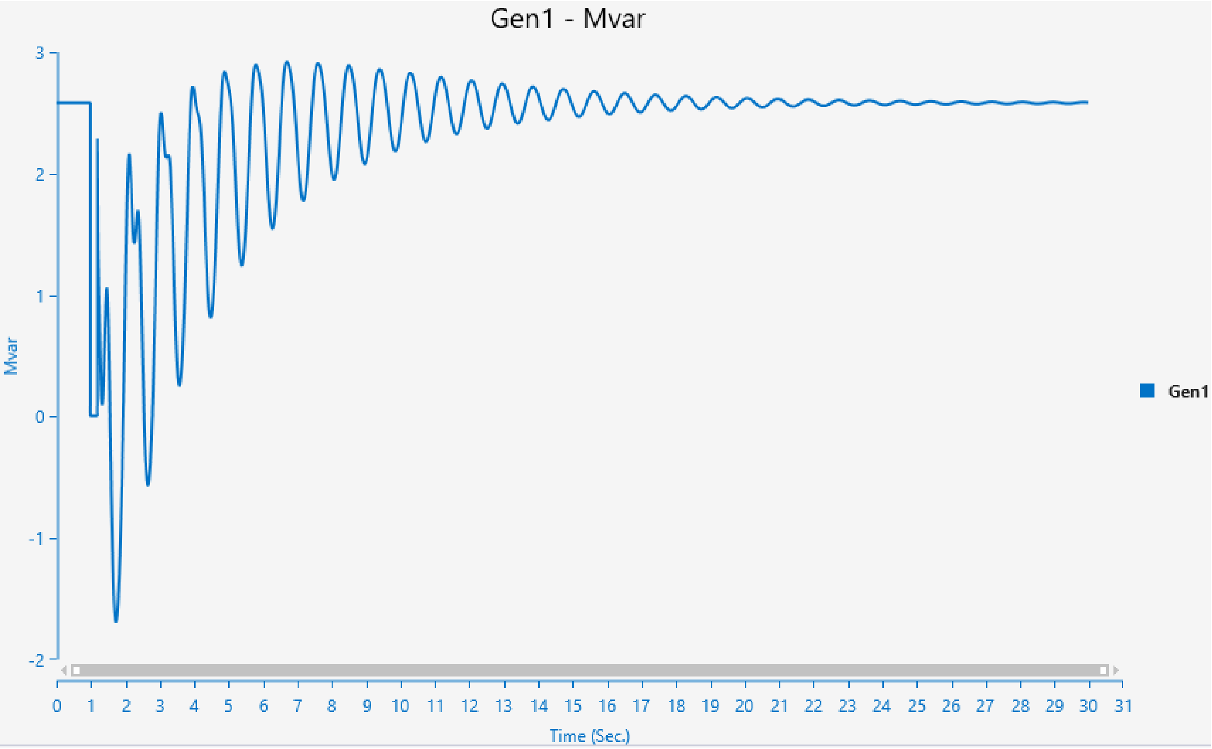


Figure 58 Generator Reactive power

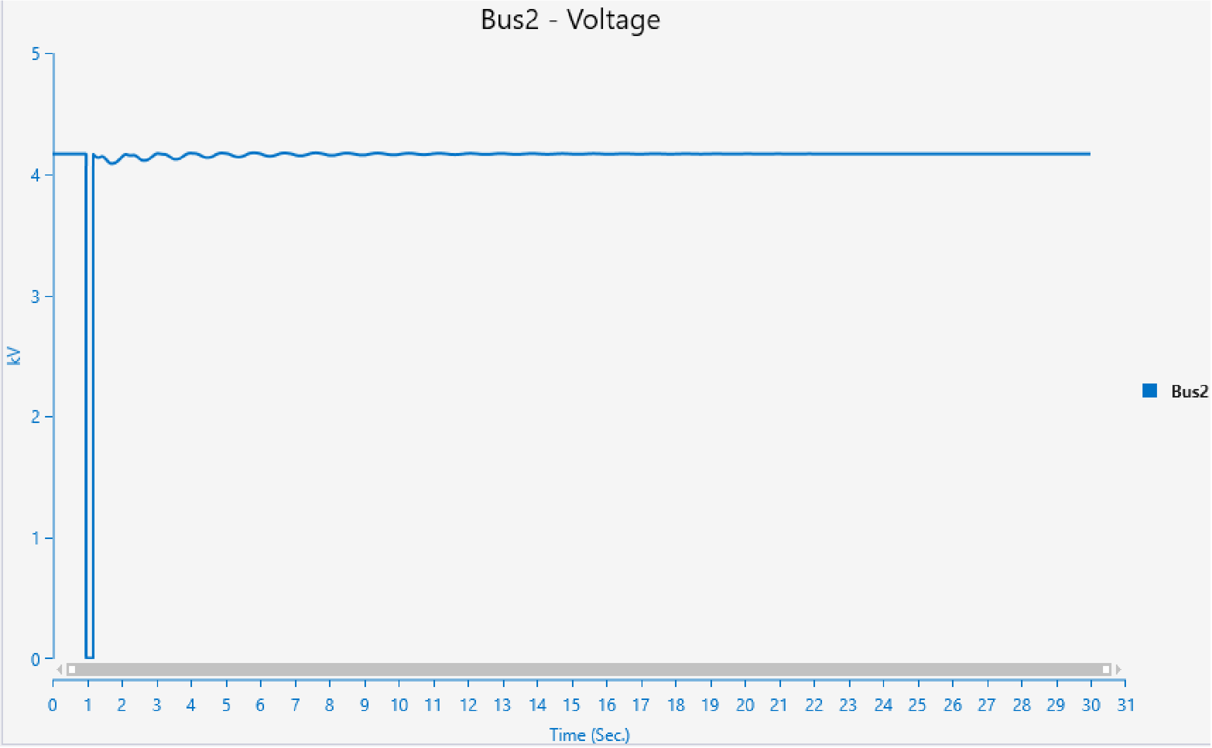


Figure 59 Bus2-Voltage

After conducting a transient stability analysis of the system after adding the wind generator and comparing it with the results that were made before adding the wind generator in the second chapter, a slight change occurred in the system and did not affect the stability of the network.

4.12.2 Case: 2

The three-phase fault is created at bus 6 for 1.00 seconds and is cleared after 1.20 seconds

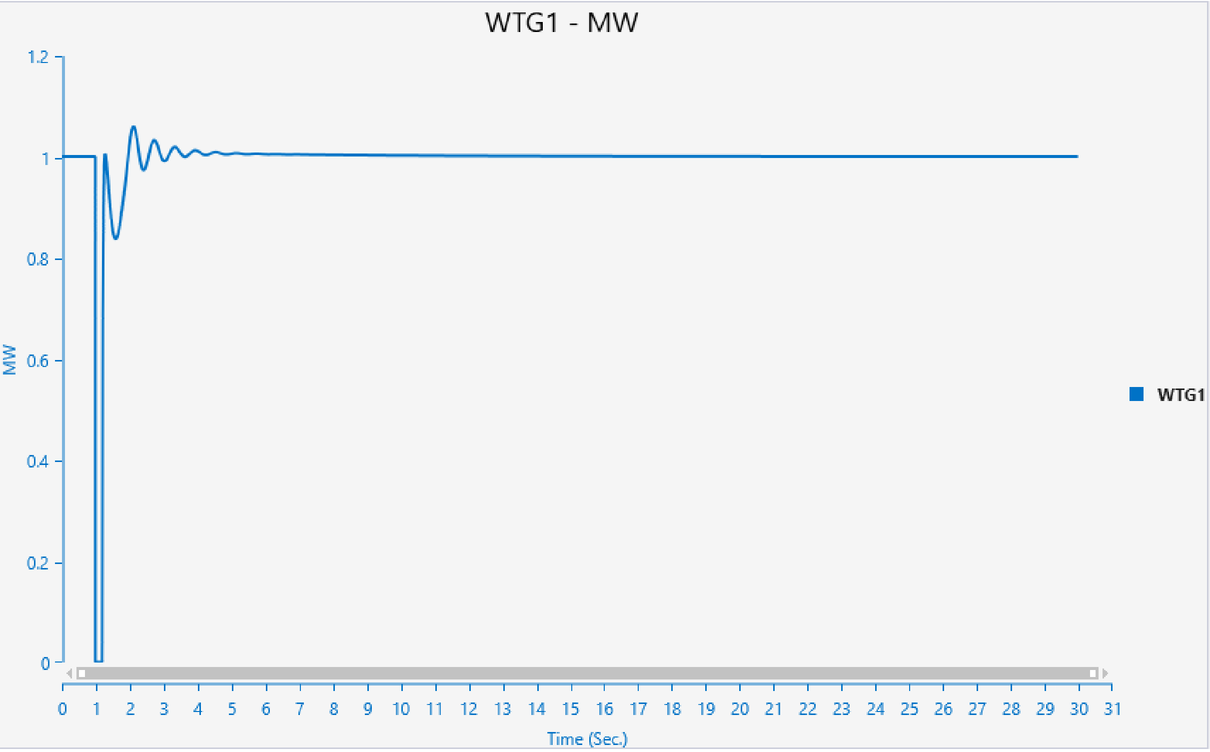


Figure 60 WTG active power (MW)

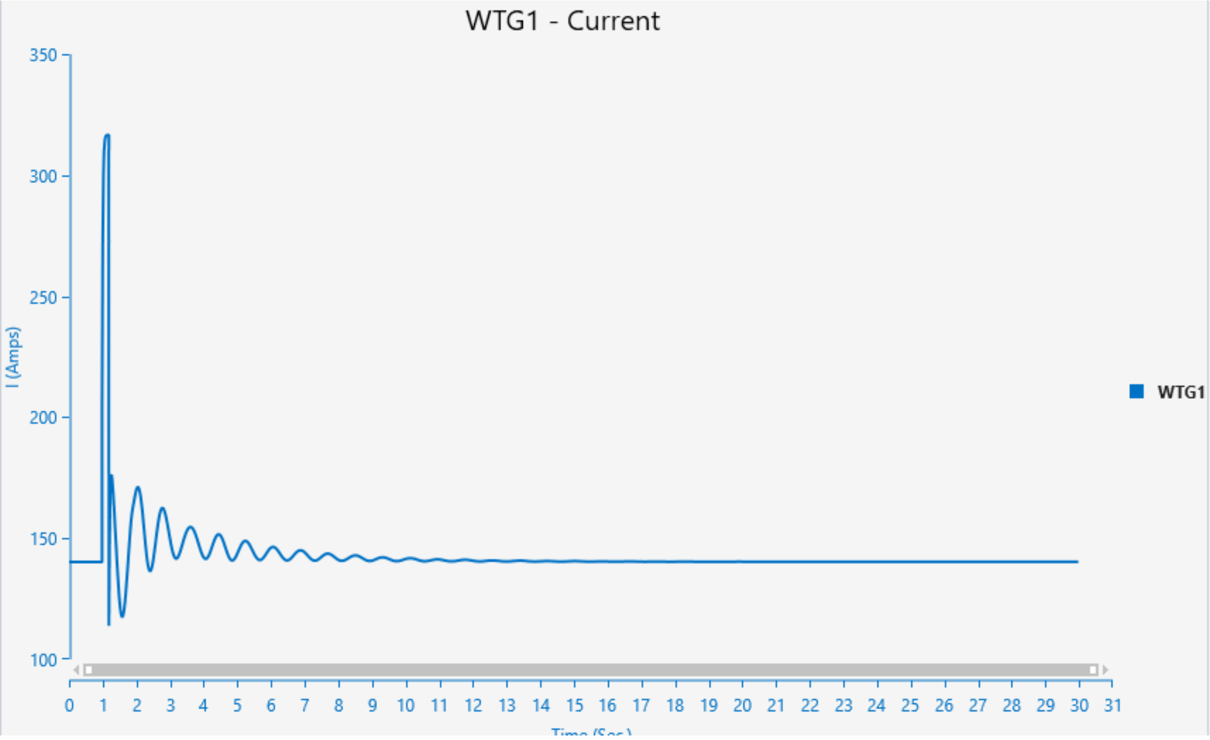


Figure 61 WTG current

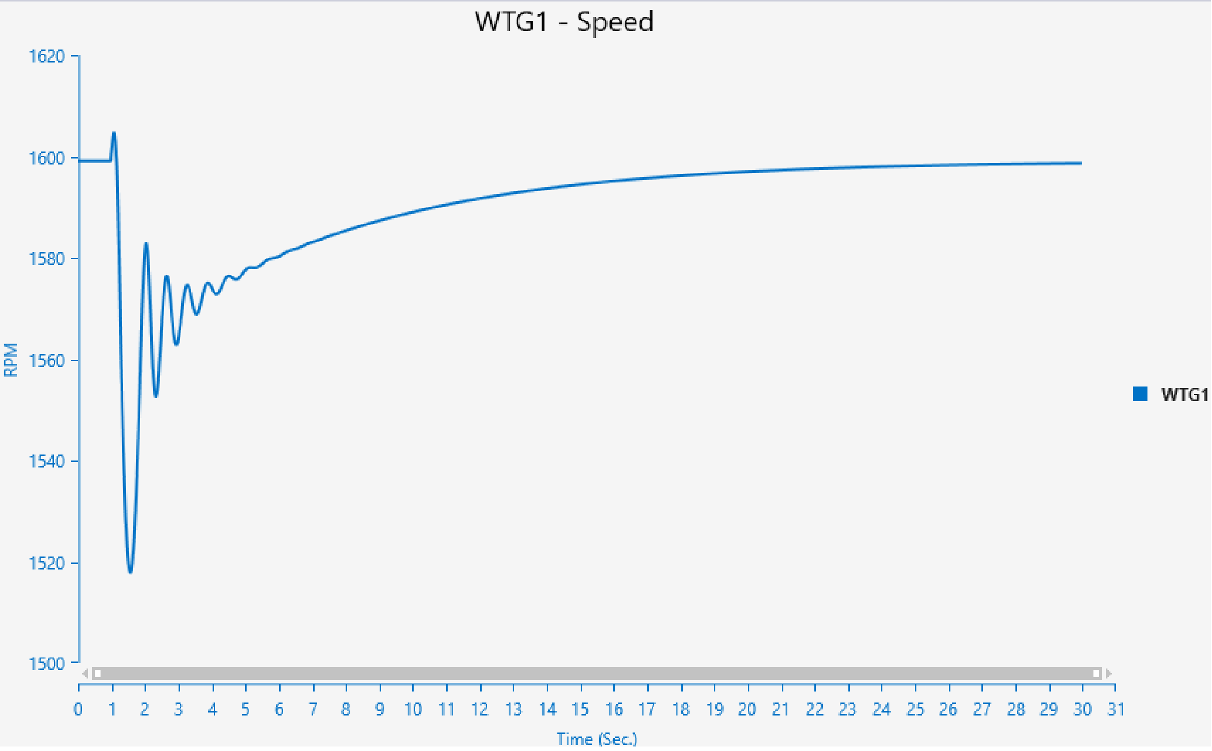


Figure 62 WTG speed

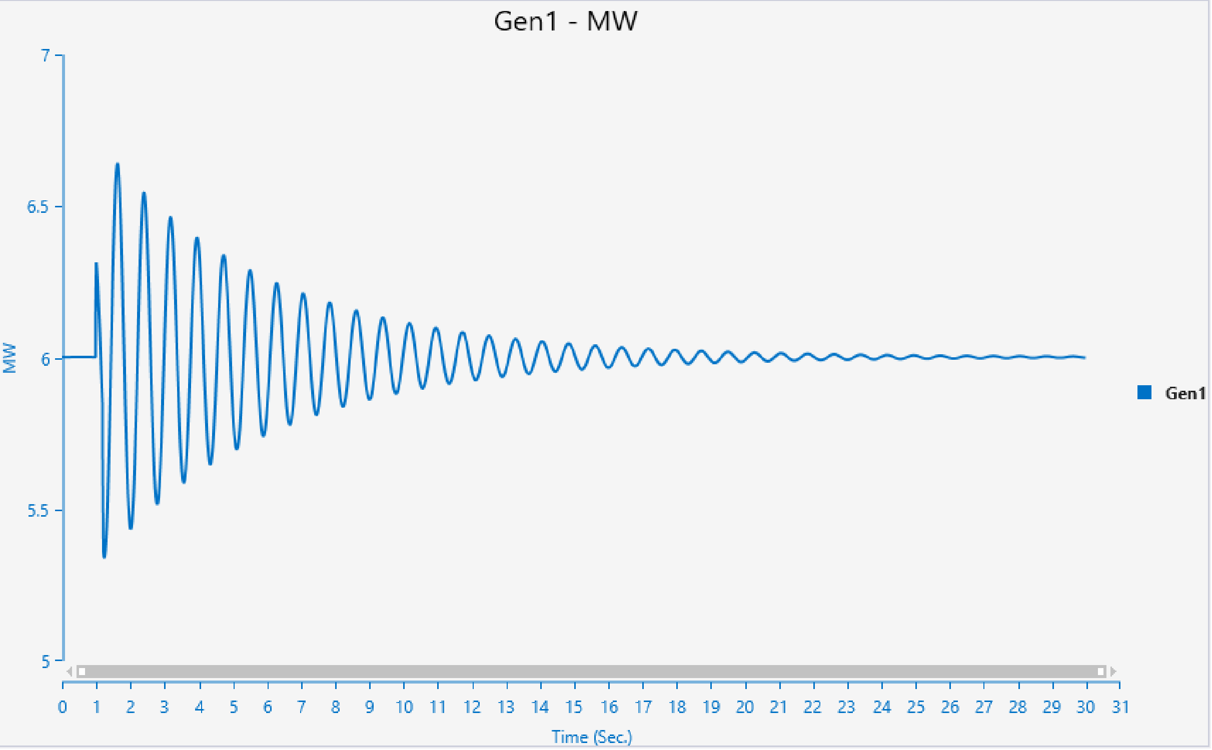


Figure 63 Generator active power (MW)

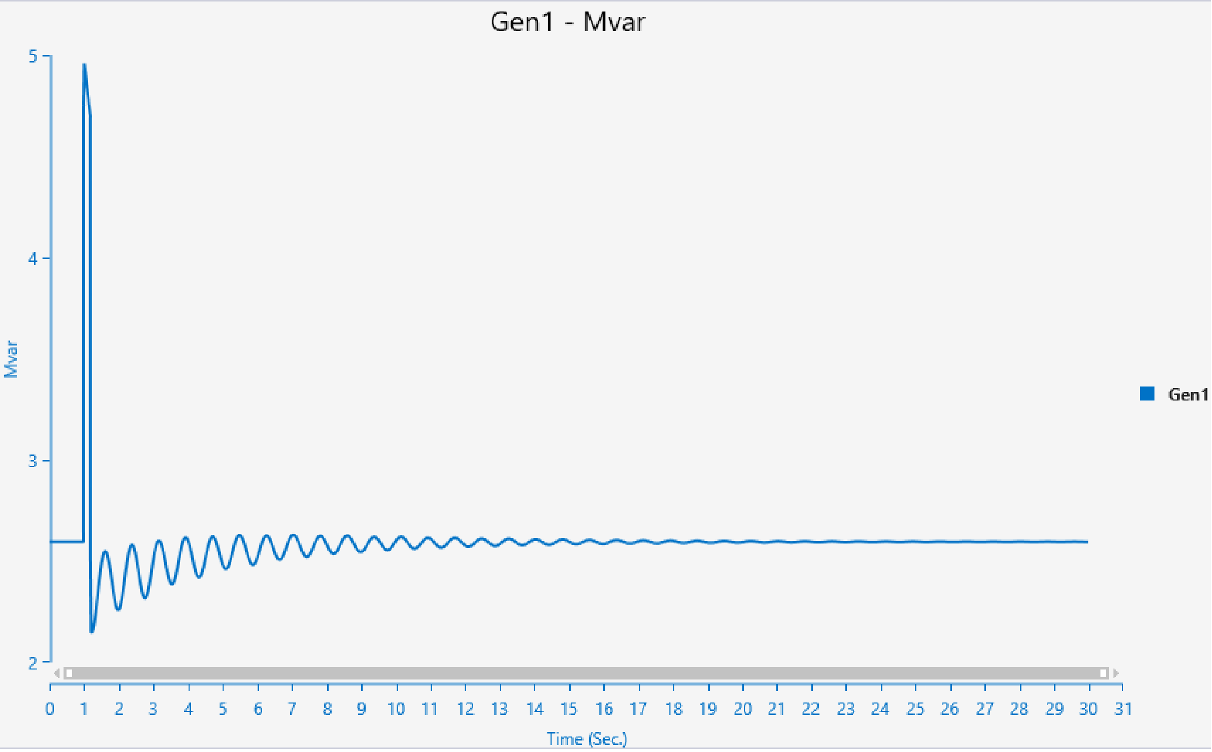


Figure 64 Generator reactive power (Mvar)

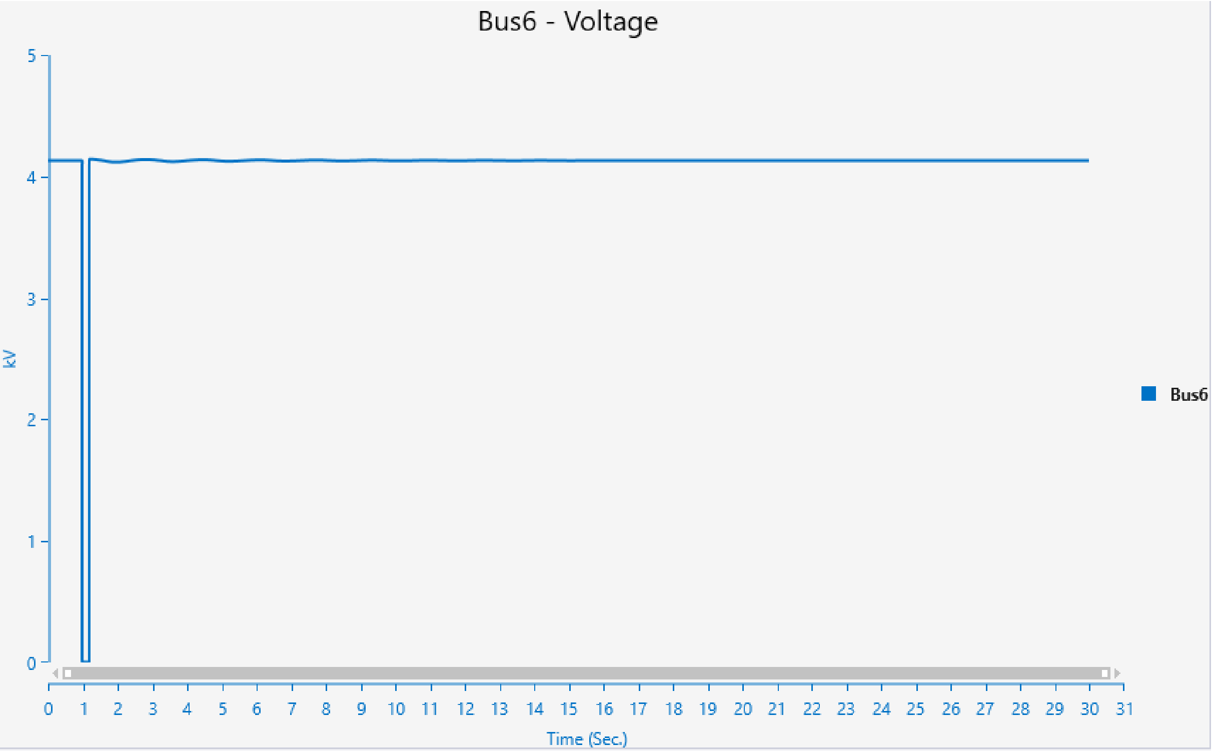


Figure 65 Bus 6 voltage

It has been used to measure the impact of the wind turbine added to the system. On the simulation that was run with the scheme occurring interference from numerous buses, the stability analysis was performed. The stability of the linked system is unaffected by disruptions to the system.

4.13 Conclusion:

This chapter presents concepts related to renewable energy systems and some concepts related to problems and challenges to the system, in addition to the results of the simulation of a system after the integration of renewable energy systems using the ETAP program.

General conclusion:

The study of the stability of the power system allowed us to know the necessity of ensuring the safe and efficient operation of electrical networks. Refers to the ability of a power system to maintain its operational state in the presence of disturbances, such as variations in load demand, equipment failures, or changes in generation output. With the increasing penetration of DERs, the dynamics of energy systems become more complex,

This study focused on the analysis of power system stability with the integration of DERs, utilizing the powerful features of ETAP software. ETAP is a widely-used and industry-standard tool that enables detailed modeling, simulation, and analysis of power systems. By leveraging the capabilities of ETAP, this study aims to assess the effects of DER integration on, short circuit and transient stability.

The results of this stability study, conducted using the ETAP software, have contributed to a deeper understanding of the challenges associated with DER integration and provide insights into effective mitigation strategies. The results can guide power system operators, engineers, and policymakers in making informed decisions related to the planning, operation, and control of power grids with high levels of DER penetration.

Finally, the study of the stability of energy systems with DER integration, using ETAP software, combines the advantages of advanced simulation and analysis tools with the complexity of modern energy systems. Leveraging the capabilities of ETAP, this research aims to advance understanding of the effects of DERs on system stability and facilitate the development of effective solutions to ensure reliable and safe integration of DERs into power grids.

References

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