Photovoltaic Integrated Power Flow Analysis

by

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A Thesis Submitted to the Academic Faculty in Partial Fulfillment of the Requirements for the Degree of

BACHELOR OF SCIENCE IN TECHNICAL AND VOCATIONAL EDUCATION WITH SPECIALISATION IN ELECTRICAL AND ELECTRONIC ENGINEERING

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Islamic University of Technology (IUT)

Gazipur, Bangladesh

November, 2017

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Acknowledgements

In the name of Allah, the most gracious and the most merciful. All praise is to Him alone. We thank Him for given us this opportunity to complete this thesis successfully.

We would like to take this opportunity to express our utmost gratitude to our thesis supervisor, Dr. Ashik Ahmed for all the assistance, guidance, and advice he has provided throughout this research endeavor.

We most strongly thank our co-supervisor Mr. Mehedi Hassan Galib, for his kind association and mentorship throughout our project.

Abstract

This work describes a steady state analysis of a building with a 6kW photovoltaic system and Generator integrated, interconnected to the grid. A power flow analysis is also known as load flow analysis in which per unit voltage and magnitude of the system is analyzed by using the Newton Raphson method and Implementation of Conventional Gauss-Seidel Method. Determines the state of the system for a load and generation given in steady state condition. Developed simulation allows predicting the steady state electrical performance of the power system incorporating a photovoltaic generator. Steady state analysis is performed using the ETAP software, with which the following types of analyzes were performed: power flow and Transient stability analysis.

The results indicate that the active power and reactive power of bus 1are within the permitted limits (86 kW, 49 kVAR) and The Transient stability analysis indicate that a 3-Phase fault occurs in bus 2 at 0.3s and the fault cleared at 0.4s.

Chapter I

1.1 Introduction

This chapter introduces the background to the impacts of integrating solar PV power and load Flow study to an existing grid. It describes the aims, vision, and scope that were used in studying the topic of solar PV power and Generator integration. It introduces the skeleton structure of the thesis report.

1.2 Background

Solar power is the production of electric power by utilizing thermal energy of sunlight rays from the sun. It consists of a solar power source and a converter of the energy from sunlight to electric energy. This power can be independent of a conventional power grid or can be integrated to an existing conventional electricity grid at transmission or distribution level. Solar power is divided into two branches of technology that are popular today. These are Concentrated Solar Power (CSP) and Photovoltaic (PV) solar power systems. Solar power in form of CSP operates similar to thermal power plants and is sometimes referred to as Concentrated Solar Thermal. It uses reflecting mirrors that reflect sunlight to a common point and heat a fluid that can further drive a turbine to generate electricity. It is an indirect solar power system. In a solar PV power, sunlight is converted to electrical energy directly by using a photovoltaic material (semiconductor material). The sun hits this material and by photovoltaic action in the material, electrical energy is generated. Concentrated Solar Power system operates like conventional thermal power plants and their effects on the grid can be understood by understanding a thermal power plant. Of much interest is the Photovoltaic (PV) solar power system that operates differently from conventional generating systems and the effects to an existing transmission or distribution system need to be fully understood before much integration can be made to any distribution or transmission system in power system.

A solar photovoltaic (PV) power system can operate in isolation or connected to a power grid. The system normally consists of a micro power source (solar) and some local loads. Additionally, it can be a solar system without any loads connected but connected to a power grid. When connected to a grid, the operating conditions of the grid are altered in either a positive or negative way. There has been a rapid increase of grid connected solar PV power in rural, urban and city areas around the globe (e.g. Sweden, Germany, India and some parts of Africa like Comoros and Nigeria …etc.). This is to enable solar PV Power systems to supply generated power locally and to other places through the existing transmission and distribution power grid. This integration of solar PV power can result in improvements of the grids or can have negative impacts on the steady state system operation parameters. Integration of solar PV power can have an impact on the active and reactive power reliability due to variations of power production and this could in turn impact on the voltage profile, voltage stability and protection of the transmission and /or Distribution power grid after integration.

A power flow study (load-flow study) is a steady-state analysis whose target is to determine the voltages, currents, and real and reactive power flows in a system under a given load conditions. The purpose of power flow studies is to plan ahead and account for various hypothetical situations. For example, if a transmission line is being taken off line for maintenance, can the remaining lines in the system handle the required loads without exceeding their rated values.

The objectives of load Flow study:

- Power flow analysis is very important in planning stages of new networks or addition to existing ones like adding new generator sites, meeting increase load demand and locating new transmission sites.
- The load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting power channels.

- It is helpful in determining the best location as well as the optimal capacity of proposed generating station, substation and new lines.
- It determines the voltage of the buses. The voltage level at the certain buses must be kept within the closed tolerances.
- System transmission loss minimizes.
- Economic system operation with respect to fuel cost to generate all the power needed
- The line flows can be known. The line should not be overloaded, it means, we should not operate the close to their stability or thermal limits.

1.3 Aim

The aim of the thesis was to investigate the impacts of integrating solar PV power and Generator to an existing distribution power grid. This was done by modelling the distribution grids with A study, was conducted that looked at the hosting capacity of PV and some integration issues in the distribution grid using ETAP and it was proposed that software such as power system simulation software could be used to further investigate the integration challenges and how much could be ok for a distribution grid. It was with that we speak in the background that the thesis was done to investigate the steady state impacts of integrating solar PV power on a distribution power grid and Generator integrated. After investigations at a minimum and maximum load demand, possible solutions to mitigating the impacts that the integration caused are proposed.

The purpose of this work is to determine through simulations the behavior in the steady state of the electrical system of the building, incorporating a photovoltaic generator of 6 kW in the main building distribution board. For this, we use ETAP™ software version 12.6.0, which is a tool of analysis, design, simulation and operation of power systems. The simulations were the following: power flow and Transient stability analysis.

1.4 Vision

Solar Energy Grid Integration Systems (SEGIS) concept will be key to achieving high penetration of photovoltaic (PV) systems into the utility grid. Advanced, integrated inverter/controllers will be the enabling technology to maximize the benefits of residential and commercial solar energy systems, both to the owners of the system and to the utility distribution network as a whole. The value of the energy provided by these solar systems will increase through advanced communication interfaces and controls, while the reliability of electrical service, both for solar and non-solar customers, will also increase.

1.5 Program Scope

The scope of the Solar Energy Grid Integration Systems (SEGIS) program includes improving the reliability and increasing the value of PV inverter/controllers while developing interfaces for advanced grid integration. SEGIS products are needed that will increase the value of solar energy systems in today's "one-way" distribution infrastructure and/or will increase the value of systems in tomorrow's two-way" grid or micro-grid. The heart of the SEGIS hardware, the inverter/controller, will manage generation and dispatch of solar energy to maximize value, reliability, and safety. The inverter/controllers will interact with building energy management systems and/or smart loads, with energy storage, and with the electric utility to allow the integration of relatively large amounts of PV energy while maintaining or increasing grid reliability.

Energy management of the future may

be integrated within inverters or

be connected via ancillary equipment (portals) that contain the necessary two-way communications to monitor, control and optimize the value of the energy produced by PV installations.

Building integration is an important feature of new designs since the complete integration of standardized PV systems with buildings optimizes the building energy balance, improves the economics of the PV system, and provides value added to the consumer and the utility.

The emphasis of the program is on developing inverter/controllers that enable integration of large amounts of PV into the electric utility distribution system.

The scope of the program includes the development of inverters/controllers for grid-interactive solar distributed generation systems that either:

incorporate energy management functions and/or power control and conversion for energy storage, or

include the ability to interface with energy management and energy storage systems, smart appliances, and utility portals, including an adaptation of these systems to communicate with and/or control the inverter/controller.

The following are not within the scope of this program:

development of photovoltaic modules,

development of energy storage devices (e.g. batteries),

non-solar-related development of energy management or energy storage systems, smart appliances, or utility portals.

SEGIS products developed under this program shall be compatible with any of the three primary PV markets segments that are connected to utility distribution systems: residential, small commercial, or commercial. Solar Energy Grid Integration Systems may be configured to address any combination of these market application segments and may be modular in nature. Take look an Example of the scale of these markets is described in Table 1.

Table 1 Applications Scale

Residential	Less than 10-kW, single-phase
Small Commercial	From 10-kW to 50-kW, typically three-phase
Commercial	Greater than 50-kW, three-phase

Chapter II

Overview of conventional load flow study

2.1 Introduction

The load flow study in a power system constitutes a study of paramount importance. The study reveals the electrical performance and power flows (real and reactive) for the specified condition when the system is operating under steady state. So, we are going to give an overview of different techniques used for load flow study.

2.2 Gauss Seidel Method

The Gauss Seidel Method (GS) is an iterative algorithm for solving a set of non-linear algebraic equations. To start with, a solution vector is assumed, based on guidance from practical experience in a physical situation. One of the equations is then used to obtain the revised value of a particular variable by substituting in it the present values of the remaining variables. The solution vector is immediately updated in respect of this variable. The process is then repeated for all the variables thereby completing one *iteration.* The iterative process is then repeated till the solution vector converges within prescribed accuracy.

Gauss-Seidel method is used to solve a set of algebraic equations.

Consider:

$$a_{11}x_1 + a_{12}x_2 + a_{1N}x_N = y_1$$

$$a_{21}x_1 + a_{22}x_2 + a_{2N}x_N = y_2$$

$$\vdots$$

$$a_{N1}x_1 + a_{N2}x_2 + a_{NN}x_N = y_N$$

Specifically

$$a_{k1} x_1 + a_{k2} x_2 + \quad + a_{kk} x_k + \quad + a_{kN} x_N = y_k$$

3.0

Thus $$a_{kk} x_k = y_k - \sum_{\substack{m=1 \\ m \neq k}}^{N} a_{km} x_m$$

This gives $$x_k = \frac{1}{a_{kk}} \left[y_k - \sum_{\substack{m=1 \\ m \neq k}}^{N} a_{km} x_m \right]$$

$k = 1,2,...,N$

In Gauss-Seidel method, initially, values of $x_1, x_2 , \; , x_N$ are assumed. Updated values are calculated using the above equation.

In any iteration h □1, up to

$m = k - 1$, values of x_m calculated in $h + 1$ iteration are used for $m = k + 1$ to N, values of x_m calculated in h iteration are used. Thus:

$$x_k^{n+1} = \frac{1}{a_{kk}} \left[y_k - \sum_{m=1}^{k-1} a_{km} \, x_m^{h+1} - \sum_{m=k+1}^{N} a_{km} x_m^{h} \right] \tag{1}$$

2.3 *Gauss-Seidel method for power flow solution*

In this method, first, an initial estimate of bus voltages is assumed. By substituting this estimate in the given set of equations, a second estimate, better than the first one, is obtained. This process is repeated and better and better estimates of the solution are obtained until the difference between two successive estimates becomes lesser than a prescribed tolerance.

First, let us consider a power system without any P-V bus. Later, the modification required to include the P-V busses will be discussed. This means that given the net power injection at all the load bus, it is required to find the bus voltages at all the load busses.

The expression of net power injection being Vk Ik*, the equations to be solved are

$$V_k I_k^* = PI_k + jQI_k \qquad for\ k = 1,2,\ldots N$$

$$k \neq s$$

In the above equations, bus currents Ik is the intermediate variables that are to be eliminated. Taking conjugate of the above equations yields (2)

$$V_k^* I_k = PI_k - jQI_k \tag{3}$$

Therefore, $I_k = \frac{PI_k - jQI_k}{V_k^*}$ (4)

From the network equations

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \ \ldots & Y_{1N} \\ Y_{21} & Y_{22} \ldots & Y_{2N} \\ \vdots & \vdots & \vdots \\ Y_{N1} & Y_{N2} \ldots & Y_{NN} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} \tag{5}$$

we can write

Ik = Yk1 V1 + Yk2 V2 + ….. + Ykk Vk + …..+ YkN VN

$$= Y_{kk} V_k + \sum_{\substack{m=1 \\ m\neq k}}^{N} Y_{km} V_m \qquad (6)$$

Combining equations (6) and (4), we have

$$Y_{kk} V_k + \sum_{\substack{m=1 \\ m\neq k}}^{N} Y_{km} V_m = \frac{PI_k - QI_k}{V_k^{*}}$$

$$\text{Thus: } V_k = \frac{1}{Y_{kk}}\left[\frac{PI_k - jQI_k}{V_k} - \sum^{N}_{\substack{m=1 \\ m\neq k \\ k=1,2,..,N \\ K\neq S}} Y_{km} V_m\right]$$

$$= \frac{PI_k - jQI_k}{Y_{kk}V_k} - \frac{\sum^{N}_{\substack{m=1 \\ m\neq k \\ k=1,2,..,N \\ K\neq S}} Y_{km} V_m}{Y_{kk}} \qquad (\mathbf{7})$$

A significant reduction in computing time for a solution can be achieved by performing as many arithmetic operations as possible before initiating the iterative calculation. Let us define

$$\frac{PI_k - jQI_k}{Y_{kk}} = A_k \qquad (\mathbf{8})$$

$$\frac{Y_{km}}{Y_{kk}} = B_{km} \qquad (\mathbf{9})$$

Having defined Ak and Bkm equation (7) becomes

A_k N

$$V_k = \frac{\quad *}{V} - \sum_{\substack{m=1\\ m\neq k}} B_{km} V_m \qquad k=1,2,,N \qquad k\neq s \qquad (10)$$

When Gauss-Seidel iterative procedure is used, the voltage at the k^{th} bu during $h+1^{th}$ iteration, can be computed as

$$V_k^{h+1} = \frac{A_k}{V_k^{h\,*}} - \sum_{m=1}^{k-1} B_{km} V_m^{h+1} - \sum_{m=k+1}^{N} B_{km} V_m^{h} \text{for} \qquad k=1,2\text{.........}N;\ k\neq s$$

2.4 Introduction to Power Flow Analysis by Newton Raphson method

It is a successive approximation procedure based on an initial unknown estimate and the use of Taylor series expansion. Comparison between two consecutive solutions is needed to see whether their difference is within the tolerance limit or not.

Power flow model of Newton Raphson method

The equations describing the performance of the network in the bus admittance form is given by:

I=YV (1)

In expanded form these equations are

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \dots & Y_{1N} \\ Y_{21} & Y_{22} \dots & Y_{2N} \\ \vdots & \vdots & \vdots \\ Y_{N1} & Y_{N2} \dots & Y_{NN} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} \qquad (2)$$

$$Y_{ij} = |Y_{ij}| \square\theta_{ij} = |Y_{ij}| \cos\theta_{ij} + j|Y_{ij}| \sin\theta_{ij} = G_{ij} + jB_{ij} \quad (3)$$

Voltage at a typical bus i is

$$V_i = |V_i| \square\delta_i = |V_i| (\cos\delta_i + j\sin\delta_i) \quad (4)$$

The current injected into the network at bus i is given by

$$\mathbf{I}_i = \mathbf{Y}_{i1}\mathbf{V}_1 + \mathbf{Y}_{i2}\mathbf{V}_2 ++ \mathbf{Y}_{iN}\mathbf{V}_n$$

$$= \sum_{i=1}^{N} Y_{in} V_{nn} \quad (5)$$

In addition to the linear network equations given equations should also be satisfied in the power flow equations introduce non- linearity into the power flow entering the network at bus, *i* is given by eqn. (1), bus power problem. These bus power model. The complex power

$$P_i + jQ_i = V_i I_i^* \quad (6)$$

Bus power equations can be obtained from the above two equations (5) and (6) by eliminating the intermediate variable I i. From eqn. (6)

$$P_i - jQ_i = V_i^* I_i = V_i^* \sum_{n=1} Y_{in} V_n = |V_i| \angle -\delta_i \sum_{n=1} |Y_{in}| \angle\theta_{in} |V_n| \angle\delta_n$$

$$= \sum_{n=1}^{N} |V_i| |V_n| |Y_{in}| \theta_{in} + \delta_n - \delta_i$$

Separating the real and imaginary parts, we obtain

$$P_i = \sum_{n=1}^{N} |V_i| |V_n| |Y_{in}| \cos(\theta_{in} + \delta_n - \delta_i) \qquad (7)$$

$$Q_i = -\sum_{n=1}^{N} |V_i| |V_n| |Y_{in}| \sin(\theta_{in} + \delta_n - \delta_i) \qquad (8)$$

The real and reactive powers obtained from the above two equations are referred as calculated powers. During the power flow calculations, their values depend on the latest bus voltages. Finally, these calculated powers should be equal to the specified powers. Thus, the non-linear equations to be solved in power flow analysis are

$$\sum_{n=1}^{N} |V_i| |V_n| |Y_{in}| \cos(\theta_{in} + \delta_n - \delta_i) = PI_i \qquad (9)$$

$$-\sum_{n=1}^{N} |V_i| |V_n| |Y_{in}| \sin(\theta_{in} + \delta_n - \delta_i) = QI_i \qquad (10)$$

It is to be noted that equation (9) can be written for bus i only if real power injection at bus i is specified.

Similarly, equation (10) can be written for bus i only if reactive power injection at bus i is specified.

N

$$\sum_{n=1} |V_i| \; V_n | \; |Y_{in}| \cos(\theta_{in} + \delta_n - \delta_i) = PI_i \qquad (9)$$

N

$$-\sum_{n=1} |V_i| \; |V_n| \; |Y_{in}| \sin(\theta_{in} + \delta_n - \delta_i) = QI_i \qquad (10)$$

Of the N total number of buses in the power system, let the number of P-Q buses be N_1 , P-V buses be N_2 . Then $N = N_1 + N_2 + 1$. Basic problem is to find the Unknown phase angles δ at the $N_1 + N_2$ number of P-Q & P-V buses and

ii) Unknown voltage magnitudes V at the N_1 number of P-Q buses.

Thus, total number of unknown variables = $2 N_1 + N_2$

We can write $N_1 + N_2$ real power specification equations (9) and N_1 reactive power specification equations (eqn.10).

Thus, total number of equations = $2 N_1 + N_2$

Therefore, Number of equations = Number of variables = $2 N_1 + N_2$

Thus, in power flow study, we need to solve the equations

N

$$\sum_{n=1} |V_i| \; |V_n| \; |Y_{in}| \cos(\theta_{in} + \delta_n - \delta_i) = PI_i \qquad (11)$$

for i = 1, 2, …….., N

$i \neq s$

and

$$-\sum_{n=1}^{N} |V_i| |V_n| |Y_{in}| \sin(\theta_{in} + \delta_n - \delta_i) = QI_i$$

for i = 1, 2, …….., N

$i \neq s$

$i \neq P - V$ buses

for the unknown variables δ_i $i = 1,2,……..,N,$ $i \neq s$ and

$|V_i|$ $i = 1,2,……..,N,$ $i \neq s$, $i \neq P - V$ buses

The unknown variables are also called as state variable

Chapter III

Stability Analysis

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. Stability involves the study of dynamics of the system about an equilibrium-initial operating condition.

power system stability is also referred to as synchronous stability and is defined as the ability of the system to return to synchronism after having undergone some disturbance due to switching on and off of load or due to line transience. To understand stability well another factor that is to be taken into consideration is the stability limit of the system. The stability limit defines the maximum power permissible to flow through a particular point or a part of the system during which it is subjected to line disturbances or faulty flow of power. Having understood these terminologies related to power system stability let us now look into the different types of stability. The synchronous stability of a power system can be of several types depending upon the nature of disturbance, and for the purpose of successful analysis it can be classified into the following 3 types as shown below: power system stability is also referred to as synchronous stability and is defined as the ability of the system to return to synchronism after having undergone some disturbance due to switching on and off of load or due to line transience. To understand stability well another factor that is to be taken into consideration is the stability limit of the system. The stability limit defines the maximum power permissible to flow through a particular point or a part of the system during which it is subjected to line disturbances or faulty flow of power. Having understood these terminologies related to power system stability let us now look into the different types of stability. The synchronous stability of a power system can be of several types depending upon the nature of disturbance, and for the purpose of successful analysis it can be classified into the following 3 types as shown below: power system stability is also referred to as synchronous stability and is defined as the ability of the system to return to synchronism after having undergone some disturbance due to switching on and off of load or due to line transience.

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The synchronous stability of a power system can be of several types depending upon the nature of the disturbance, and for the purpose of successful analysis it can be classified into the following 3 types as shown below:

In our study we will focus on:

1 Steady-State Stability

2 Transient Stability

3 Dynamic Stability

Steady state stability of power systems results from gradual system changes.

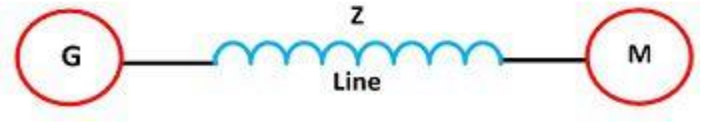
- Steady state stability is the ability of the power system network to remain or to stay in equilibrium following a gradual system change.

Example: Gradual load increase as in the addition of MW at load terminals or in gradual load decrease, as in steam change at the prime mover power. Power systems in general and alternators, in particular, have steady state stability limit beyond which if subjected to gradual load changes will loss steady state stability. The power system is capable to resist the changes that occur after the disturbance and hence remain in the stable form that is capable of maintaining equilibrium.

When all the machines in one part run together, then they are treated as one large machine connected at that point. Even, if the machines are not connected to the same bus bar and are separated by large reactance, they are also considered a large machine.

The large system in a power system is always supposed to have a constant voltage and is treated as an infinite bus.

Consider a system consists a generator G, transmission line and a synchronous motor M in the form of a load



The expression below gives the maximum power generated by the generator G and synchronous motor PD= $\frac{D}{B}VG2Cos(B-D)+\frac{VG\,VM}{b}$

$$\text{PD} = \frac{VGVM}{B} - \frac{A}{B}VM2Cos(b-B)$$

The expression below gives the maximum power generated by the generator G and synchronous motor M

$$\text{PD} = \frac{D}{B}VG2Cos(B-D) + \frac{VGVM}{b}$$

$$\text{PMMax} = \frac{VGVM}{b} - \frac{A}{B}VM2Cos(B-D)$$

$$PMax = \text{PM} - \text{PG} =$$

$$P = PM - PG = \frac{\text{VGVM}}{\text{X}}Sind$$

$$PMax = \frac{\text{VGVM}}{\text{X}}$$

Transient stability of a power system refers to the ability of the system to reach a stable condition following a large disturbance in the network condition. In all cases related to large changes in the system like sudden application or removal of the load, switching operations, line faults or loss due to excitation the transient stability of the system comes into play. It infarct deals in the ability of the system to retain synchronism following a disturbance sustaining for a reasonably long period of time. And the maximum power that is permissible to flow through the network without loss of stability following a sustained period of disturbance is referred to as the transient stability of the system. Going beyond that maximum permissible value for power flow, the system would temporarily be rendered as unstable. The preceding look at steady-state stability serves as a background for an examination of the more complicated problem of transient stability. This is true because the same three electrical characteristics that determine steady-state stability limits affect transient stability. However, a system that is stable under steady-state conditions is not necessarily stable when subjected to a transient disturbance. Transient stability means the ability of a power system to experience a sudden change in generation, load, or system characteristics without a prolonged loss of synchronism. To see how a disturbance affects a synchronous machine, consider the steady-state characteristics described by the steady-state torque equation first.

$$T = \frac{\text{�}P2}{8} \varphi SRFRSin\ \delta R$$

T is the mechanical shaft torque

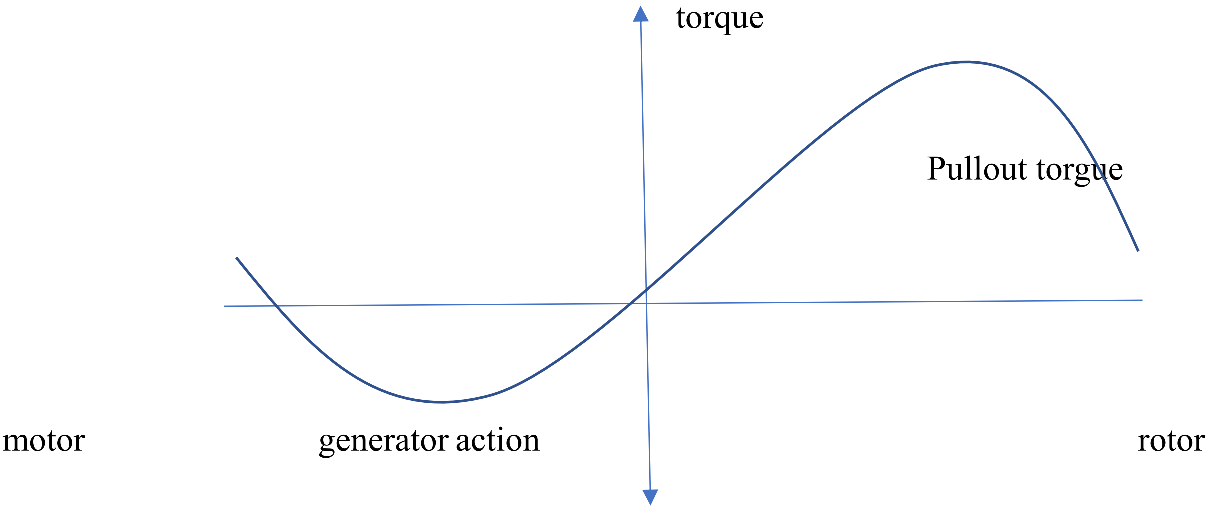
P is the number of poles of machine

φ SR is the air-gap flux

FR is the rotor field MMF

δ R is the mechanical angle between rotor and stator field lobes

The air-gap flux φ SR stays constant as long as the internal voltage (which is directly related to field excitation) at the machine does not change and if the effects of saturation of the iron are neglected. Therefore, if the field excitation remains unchanged, a change in shaft torque T will cause a corresponding change in rotor angle δ R. (This is the angle by which, for a motor, the peaks of the rotating stator field lead the corresponding peaks of the rotor field. For a generator, the relation is reversed.) Figure 4 graphically illustrates the variation of rotor angle with shaft torque. With the machine operating as a motor (when rotor angle and torque are positive), torque increases with rotor angle until δ R reaches 90 electrical degrees. Beyond 90°, torque decreases with increasing rotor angle. As a result, if the required torque output of a synchronous motor is increased beyond the level corresponding to 90° rotor angle, it will slip a pole. Unless the load torque is reduced below the 90° level (the pullout torque), the motor will continue slipping poles indefinitely and is said to have lost synchronism with the supply system (and become unstable).



Rotor angle relationship for synchronous machines in steady state A generator operates similarly. Increasing torque input until the rotor angle exceeds 90° results in pole slipping and loss of synchronism with the power system, assuming constant electrical load. Similar relations apply to the other parameters of the torque equation. For example, air-gap flux φ SR is a function of the voltage at the machine. Thus, if the other factors remain constant, a change in system voltage will cause a change in rotor angle. Likewise, changing the field excitation will cause a change in rotor angle if constant torque and voltage are maintained. The preceding discussion refers to rather gradual changes in the conditions affecting the torque angle so that approximate steady-state conditions always exist. The coupling between the stator and rotor fields of a synchronous machine, however, is somewhat elastic. This means that if an abrupt rather than a gradual change occurs in one or more of the parameters of the torque equation, the rotor angle will tend to overshoot the final value determined by the changed conditions. This disturbance can be severe enough to carry the ultimate steady-state rotor angle past 90° or the transient swing rotor angle past 180°. Either event results in the slipping of a pole. If the conditions that caused the original disturbance are not corrected, the machine will then continue to slip poles; in other words, pulling out of step or loosing synchronism with the power system to which it is connected. Of course, if the transient overshoot of the rotor angle does not exceed 180°, or if the disturbance causing the rotor swing is promptly removed, the machine may remain in synchronism with the system. The rotor angle then oscillates in decreasing swings until it settles to its final value (less than 90°). The oscillations are damped by the electrical load as well as mechanical and electrical losses in the machine and system, especially in the damper windings of the machine.

Chapter IV

Power System Fault

4.1 Introduction

A fault is any abnormal condition in a power system. The steady state operating mode of a power system is balanced 3-phase a.c. However, due to sudden external or internal changes in the system, this condition is disrupted. When the insulation of the system fails at one or more points or a conducting object comes into contact with a live point, a short circuit or a fault occurs.

4.2 Causes

The causes of faults are numerous, e.g. Lightning, Heavy winds, Trees falling across lines, Vehicles colliding with towers or poles, Birds shorting lines, Aircraft colliding with lines, Vandalism, Small animals entering switchgear, Line breaks due to excessive loading.

4.3 Common power system faults

Power system faults may be categorized as one of four types; in order of frequency of occurrence, they are:

- Single line to ground fault
- Line to line fault
- Double line to ground fault
- Balanced three phase faults

The first three types constitute severe unbalanced operating conditions which involves only one or two phases hence referred to as unsymmetrical faults. In the fourth type, a fault involving all the three phases occurs therefore referred to as symmetrical (balanced) fault.

4.4 Effects of power system faults

Faults may lead to fire breakout that consequently results into loss of property, loss of life and destruction of a power system network. Faults also leads to cut of supply in areas beyond the fault point in a transmission and distribution network leading to power blackouts; this interferes with industrial and commercial activities that supports economic growth, stalls learning activities in institutions, work in offices, domestic applications and creates insecurity at night. All the above results into retarded development due to low gross domestic product realized. It is important therefore to determine the values of system voltages and currents during faulted conditions, so that protective devices may be set to detect and minimize the harmful effects of such contingencies

Balanced three phase faults may be analyzed using an equivalent single-phase circuit. With asymmetrical three phase faults, the use of symmetrical components helps to reduce the complexity of the calculations as transmission lines and components are by and large symmetrical, although the fault may be asymmetrical. Fault analysis is usually carried out in per-unit quantities (similar to percentage quantities) as they give solutions which are somewhat consistent with different voltage and power ratings, and operate on values of the order of unity.

In the ensuing sections, we will derive expressions that may be used in computer simulations by the utility Equivalent Circuits - Single phase and Equivalent Single-Phase Circuits In a balanced three phase circuit, since the information relating to one single phase gives the information relating to the other two phases as well, it is sufficient to do calculations in a single-phase circuit. There are two common forms used. These are (i) to take any one single phase of the three-phase circuit and (ii) to take an equivalent single-phase circuit to represent the full three phase circuit.

4.5 Single Phase Circuit

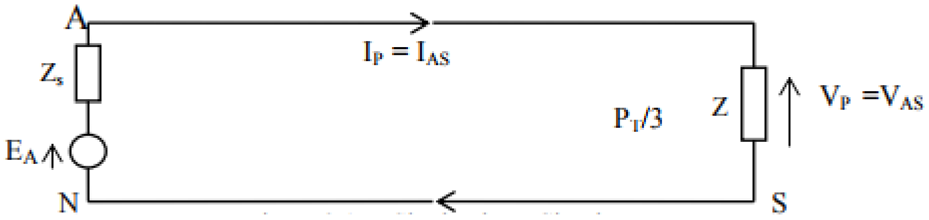


Fig 4.1: Single Phase Circuit (Prof J Rohan Lucas)

Figure 4.1 shows one single phase “AN” of the three-phase circuit “ABC N”. Since the system is balanced, there is no current in the neutral, and there is no potential drop across the neutral wire. Thus, the star point “S” of the system would be at the same potential as the neutral point “N”. Also, the line current is the same as the phase current, the line voltage is √3 times the phase voltage, and the total power is 3 times the power in a single phase.

I = IP = IL, V = VP = VL/√3 and S = SP = ST/3

Working with the single-phase circuit would yield single phase quantities, which can then be converted to three phase quantities using the above conversions.

Equivalent Single-Phase Circuit Of the parameters in the single-phase circuit shown in figure 4.1, the Line Voltage and the Total Power (rather than the Phase Voltage and one-third the Power) are the most important quantities. It would be useful to have these quantities obtained directly from the circuit rather than having conversion factors of √3 and 3 respectively. This is achieved in the Equivalent Single-Phase circuit, shown in figure 4.2, by multiplying the voltage by a factor of √3 to give Line Voltage directly.

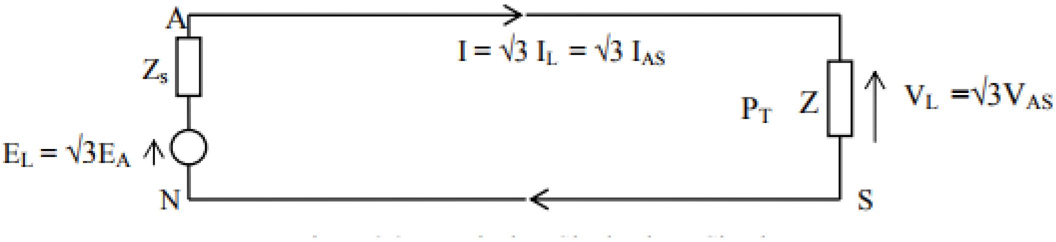


Fig 4.2: Equivalent single-phase circuit (Prof J Rohan Lucas)

The Impedance remains as the per-phase impedance. However, the Line Current gets artificially amplified by a factor of √3. This also increases the power by a factor of $(\sqrt{3})^2$, which is the required correction to get the total power. Thus, working with the Equivalent single-phase circuit would yield the required three phase quantities directly, other than the current which would be √3 IL.

Per unit quantities, like percentage quantities, are actually fractional quantities of a reference quantity. These have a lot of importance as per unit quantities of parameters tend to have similar values even when the system voltage and rating change drastically. The per unit system permits multiplication and division in addition to addition and subtraction without the requirement of a correction factor (when percentage quantities are multiplied or divided additional factors of 0.01 or100 must be brought in, which are not in the original equations, to restore the percentage values). Per-unit values are written with “pu” after the value. For power, voltage, current and impedance, the per unit quantity may be obtained by dividing by the respective base of that quantity.

$$\mathrm{S\ pu} = \frac{S}{Sbase} \quad Vpu \ \frac{\mathrm{V}}{Vbase} \quad Ipu \frac{\mathrm{I}}{Ibase} \quad Zpu = \frac{\mathrm{Z}}{\mathrm{Zbase}}$$

Expressions such as Ohm’s Law can be applied for per unit quantities as well. Since Voltage, Current, Impedance, and Power are related, only two Base or reference quantities can be independently defined. The Base quantities for the other two can be derived there from. Since Power and Voltage are the most often specified, they are usually chosen to define the independent base quantities.

Calculation for Single Phase Systems If VAbase and Vbase are the selected base quantities of power (complex, active or reactive) and voltage respectively, then

$$\text{Base current} \quad \mathrm{Ibase}= \frac{VbaseIbase}{Vbase} = \frac{VAbase}{Vbase}$$

$$\text{Base Impedance Zbase} = \frac{Vbase}{Ibase} = \frac{V^2\ base}{IbaseVbase} = \frac{V^2 base}{VAbase}$$

In a power system, voltages and power are usually expressed in kV and MVA, thus it is usual to select an MVAbase and a kVbase and to express them as

$$\text{Base current} \qquad \mathrm{Ibase}= \frac{MVAbase}{KVbase} \quad in\ KA, \quad [10^6/10^3 = 10]$$

$$\text{Base Impedance} \qquad \mathrm{Zbase}= \frac{KV^2 base}{MVAbase} \quad in\ \Omega \quad [= (10^3)/10^6 = 1]$$

In these expressions, all the quantities are single phase quantities.

Chapter V

Power System Studies

5.1 Introduction

A load flow analysis was carried out Using ETAP software which uses the buses voltages, the flow of current and power in the system, and branches power factor to perform load flow analysis. ETAP software has been designed to be able to perform different types of load flow analysis based on the custom choices and purposes.

The purpose of load flow analysis in ETAP is to have a broad idea about the behavior of the power system under different load conditions. It helps a power system engineer to design and test the performance of their systems before they were installed. It provides a real-time simulation operation of the power system. It can also be used predict possible power system problems that may happen in the future so that proper arrangements/plans can be put in place. The load flow Study is capable to define and adjust the parameters of the system for each case separately. ETAP has multiple choices to define the display options based on the user's needs and requirements for load flow analysis.

5.2 Load flow Simulation Using ETAP

The implementation of load flow analysis using ETAP with a transformer rating of 75kVA been supplied by a voltage of 11400V bus 1 from the grid. The voltage was stepped down by the transformer to 208V. THHN cable of length 60 meters was connected and low voltage circuit breaker between 208V bus 2 and 208V bus 3. The bus 3 carries a load of 60kVA.

From figure 5.1 we can see that the voltage at 11400V bus 1 before the transformer was at 11400V which account for 100% of the rated voltage and the real and reactive power were 52 kW and 34 kVar respectively. The analysis has shown that the voltage at bus 2 was 203V and the real power was 51 kW while the reactive power was 32 kVar. Similarly, at bus 3 198.8V was recorded 50 kW and 31 kVar was recorded for the real and reactive power.

When a PV was integrated as shown in figure 5.2, the voltage at 11400V bus 1 before the transformer was at 11400V which account for 100% of the rated voltage and the real and reactive power was 46 kW and 33 kVar respectively. The analysis has shown that the voltage at bus 2 was 203.3V and the real power was 46 kW while the reactive power was 32 kVar. Similarly, at bus 3 199.3V was recorded and 50 kW and 31 kVar was recorded for the real and reactive power. Similarly, the PV was supplying real power of 5 kW and 0 kVar.

The results have shown that integrating a PV system into network improves the system voltage profile as can be observed in the busses. The importance of the load flow analysis is to make sure that the network is safe enough to be connected with PV generators.

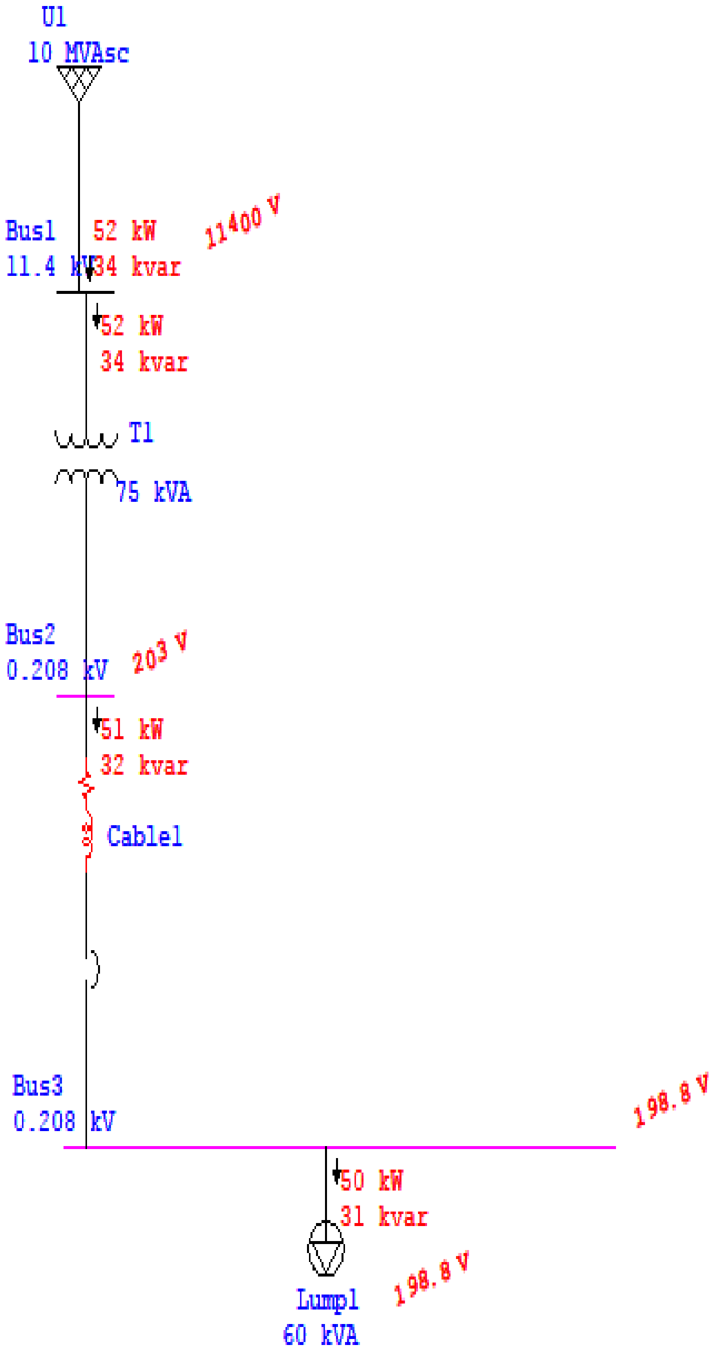


Figure 5.1: Load Flow Analysis Simulation

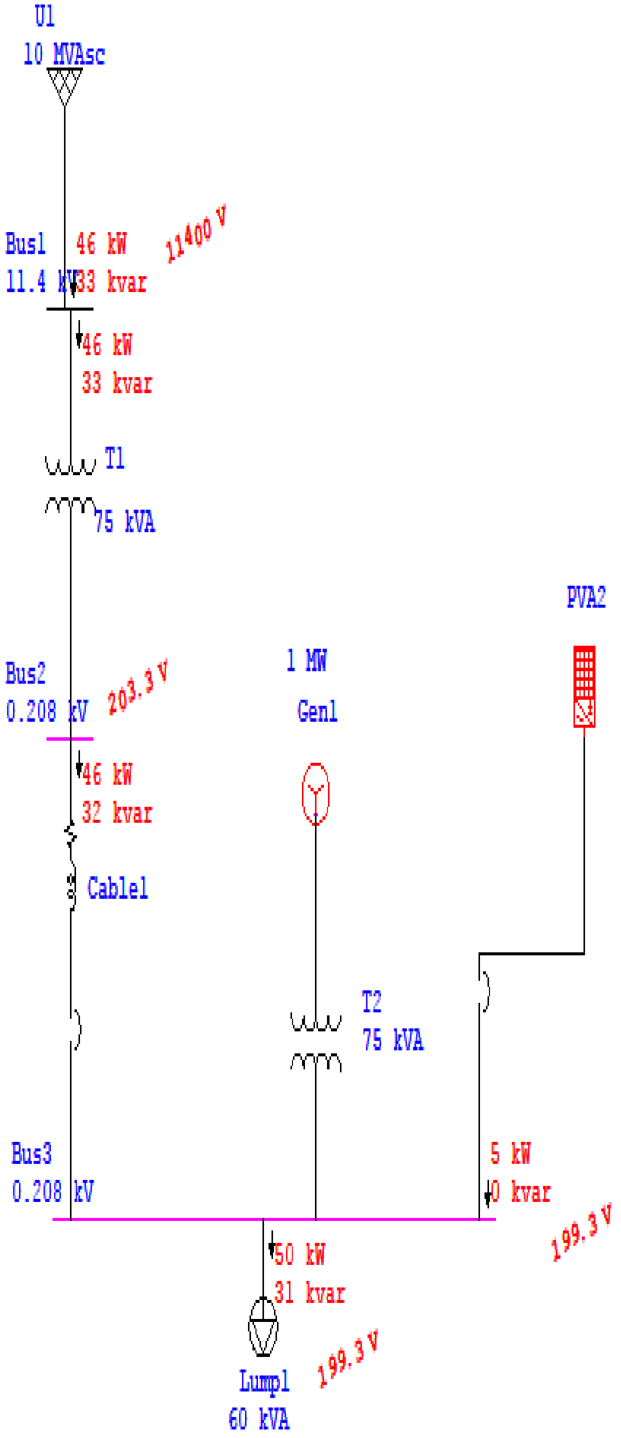


Figure 5.2: Load Flow Analysis Simulation with PV and Generator Integrated

5.3 Transient Stability Analysis

The ETAP is designed to study the system's dynamic behavior and steady state limits of a power system. This analysis is implemented before, during, and after disturbances in the electric systems. The program implements the activities defined by the user to analyses the system. It also determines the type of response by the system to these predetermined events. These analyses are important to determine the protective and design parameters of the system.

Voltage state is the numerical description of the system voltages at a given point, generally a bus of the electric system at some determined circumstances. A voltage state can be pre-load state, small load state, a full load state, and finally, overload state. In power systems, voltage is limited to predefined values that shouldn't be exceeded. Some differences in the voltage state parameters can lead the system to be unstable. Voltage stability is a description of the ability of the system
to preserve steady state parameters and voltages at their state values after different faults or occurrences (Cutsem & Vournas, 1998).

5.4 Case Study: Varying Condition by Changing the System Load Demand

A case was studied by varying the system load between 100 kVA and 200 kVA and transient stability analysis was simulated to study the effect the load had in the system under different condition. A 3-Phase fault occurred at 208V bus 2 at time 0.3s while the fault clearing time was at time 0.4s. The total time taken between the occurrence of the fault and fault clearing time was 0.1s. The system was studied under pre-fault, at fault, and post fault as shown in figure 5.3 through 5.8.

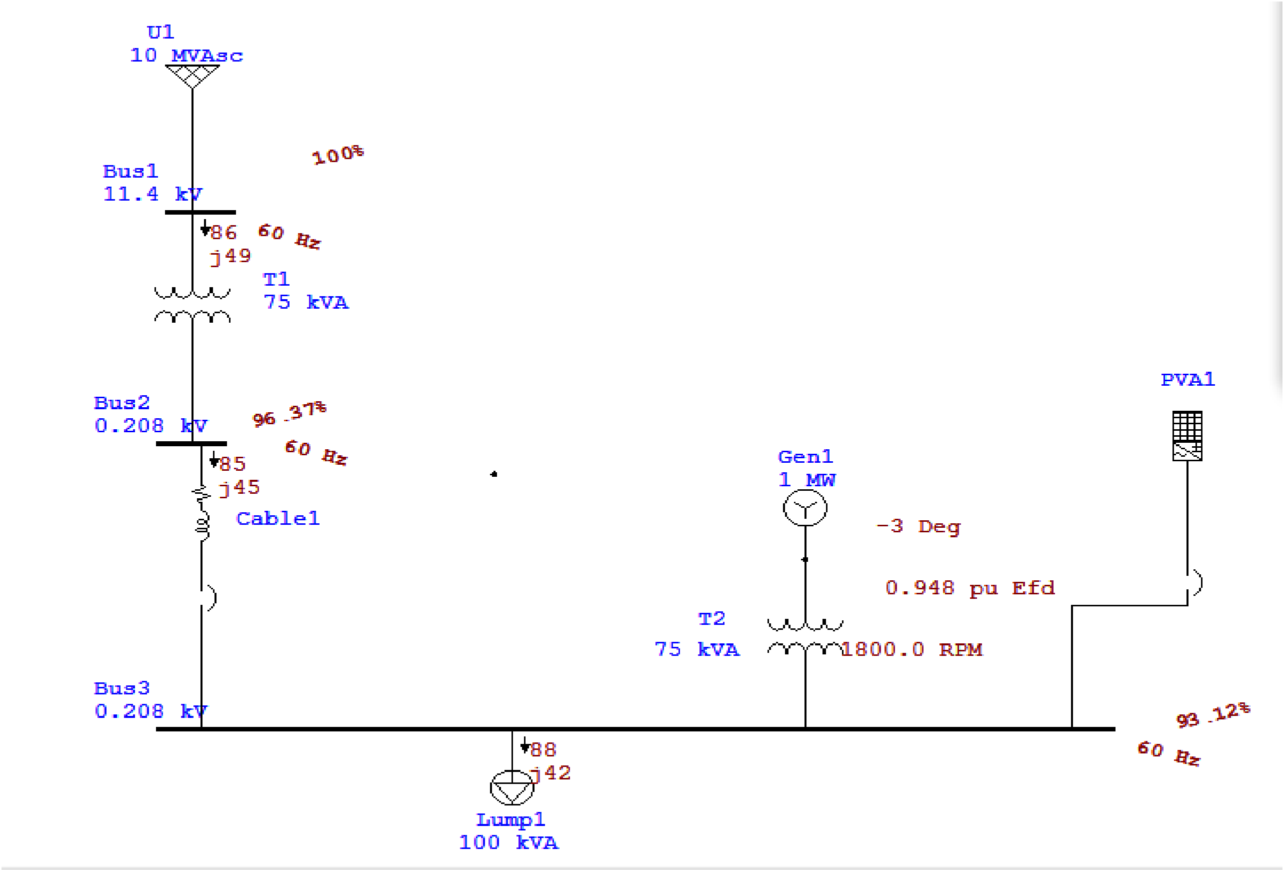


Figure 5.3: Transient Analysis Simulation at 100kVA Load Before Occurrence of Fault.

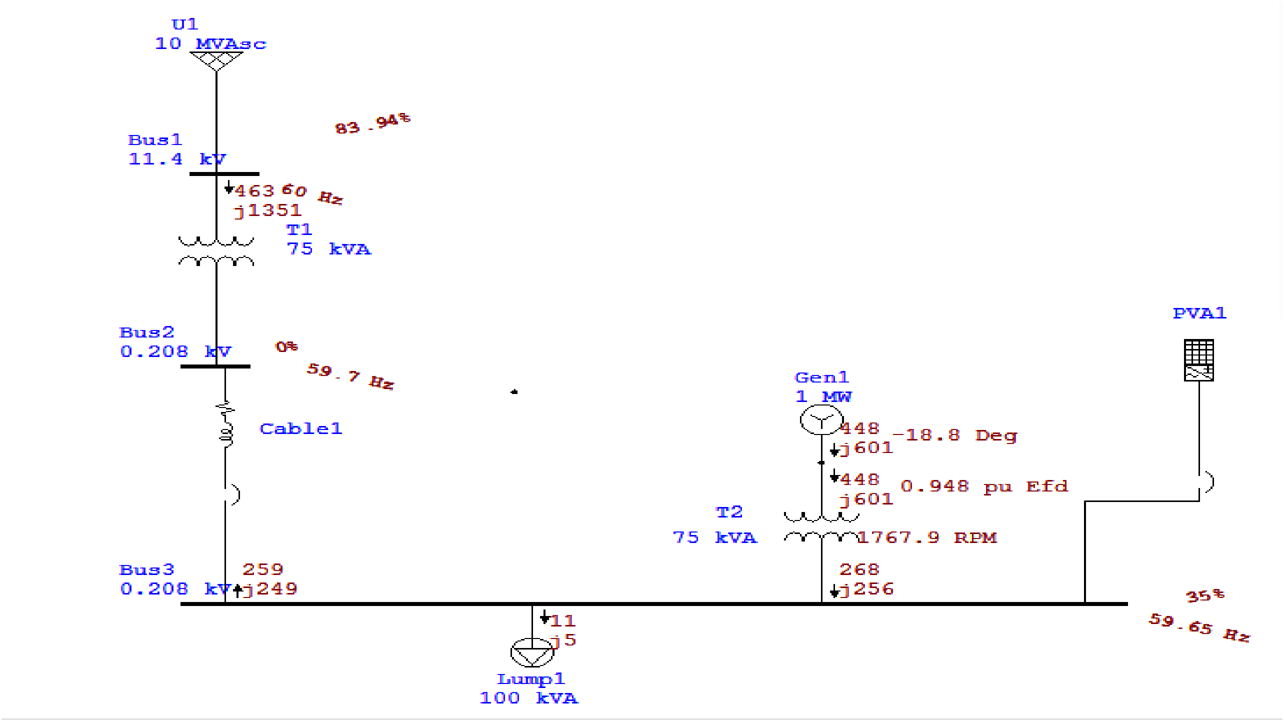


Figure 5.4: Transient Analysis Simulation at 100kVA Load During Fault Condition.

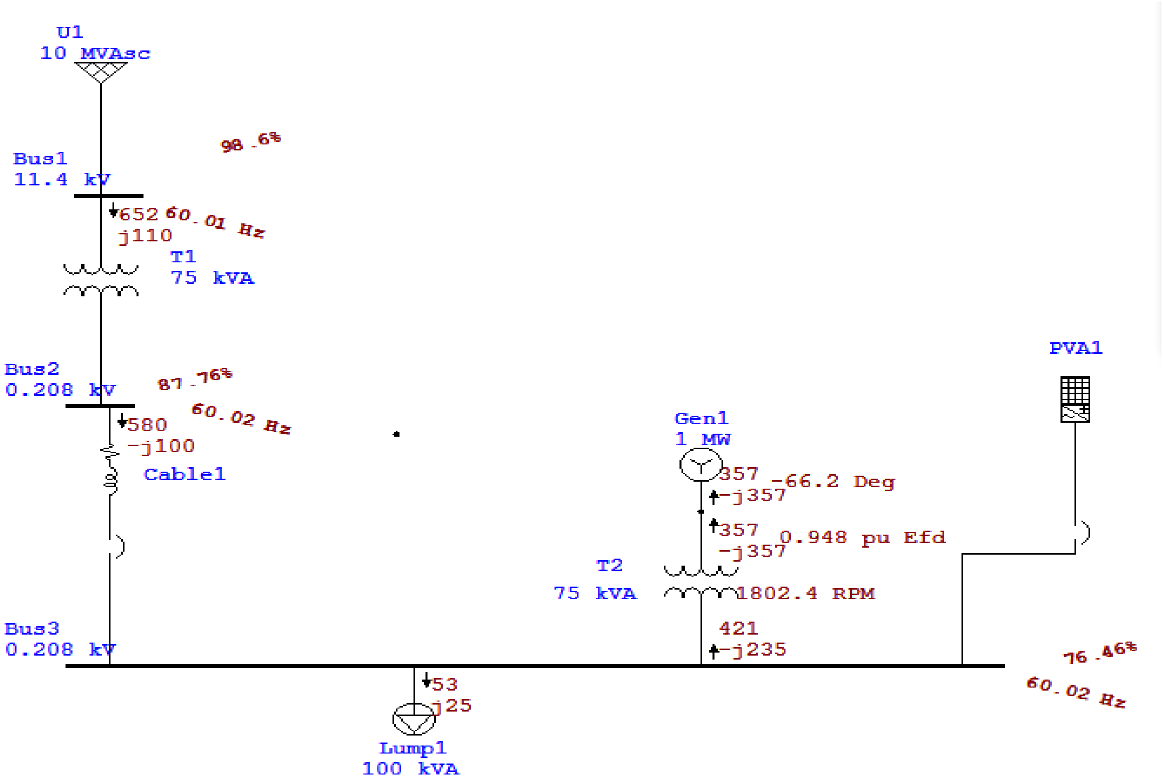


Figure 5.5: Transient Analysis Simulation at 100kVA Load After Occurrence of Fault

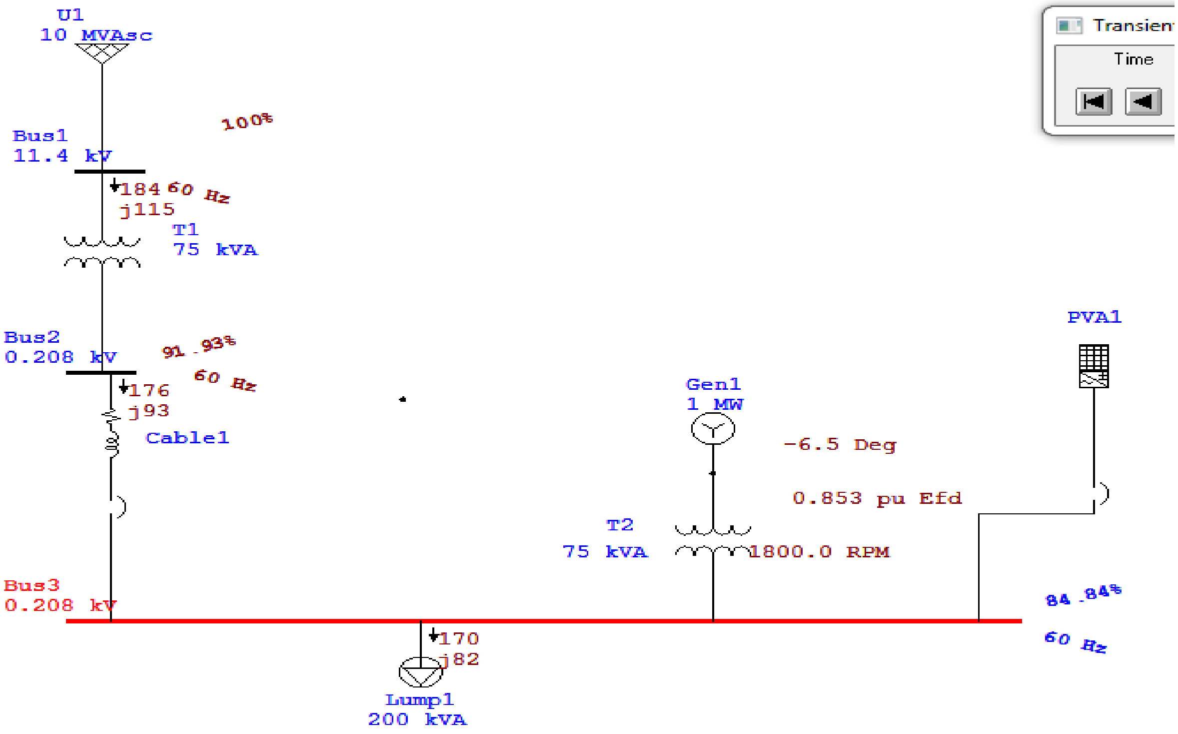


Figure 5.6: Transient Analysis Simulation at 200kVA Load Before Occurrence of Fault

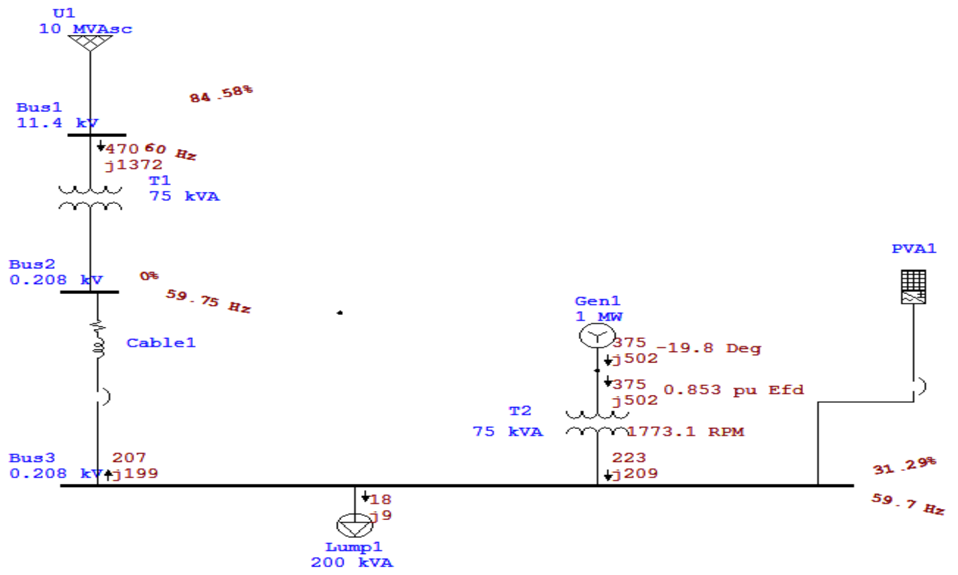


Figure 5.7: Transient Analysis Simulation at 200kVA Load During Fault Condition

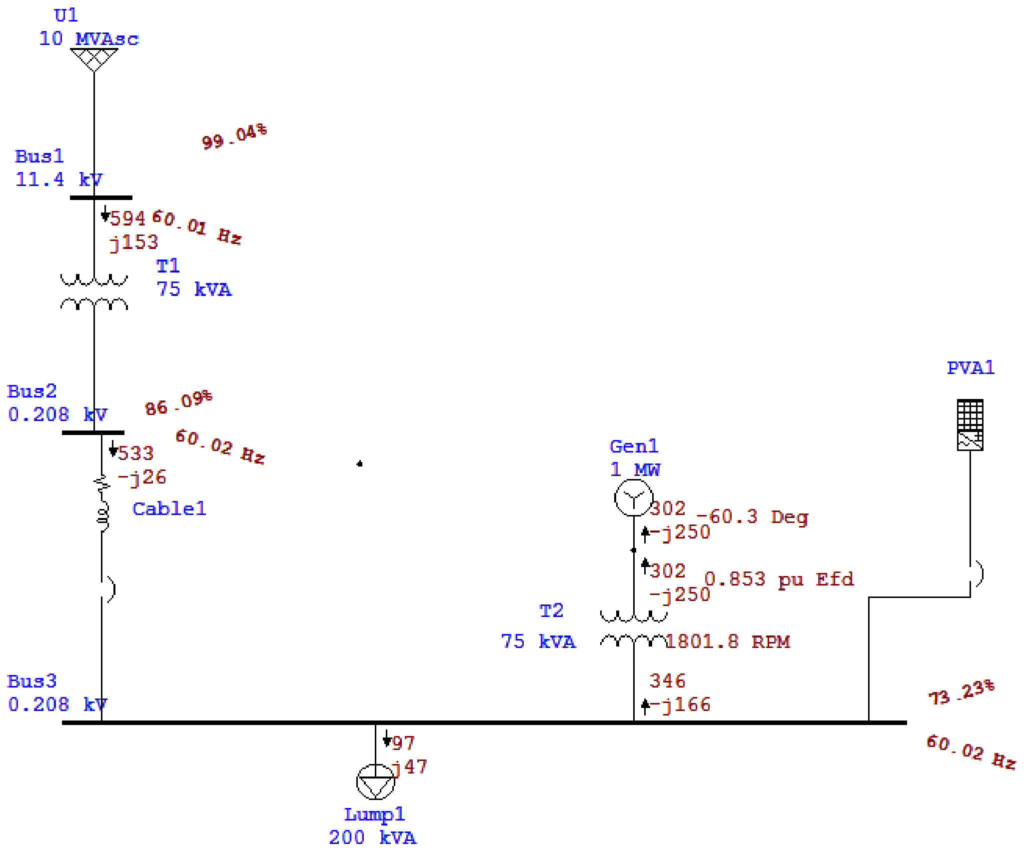


Figure 5.8: Transient Analysis Simulation at 200kVA Load After Occurrence of Fault

In transient stability, we studied the behavior of the system under consideration during the disturbance for a small interval in both cases of the load. The results are shown in Figure 5.3 through Figure 5.8. The figures show the transient voltage that follows after varying the load voltage.

From figure 5.9, the absolute power angle of the generator at 100kVA load was around -3 degrees. The generator relative power angle was also around -3 degrees similar to that of the absolute power angle as seen in figure 5.10. The generator frequency maintains its synchronism.

At 200kVa load shown in figure 5.12, the absolute power angle of the generator was around -6.5 degrees. The generator relative power angle was also around -6.5 degrees similar to that of the absolute power angle as seen in figure 5.13, The generator frequency maintains its synchronism.

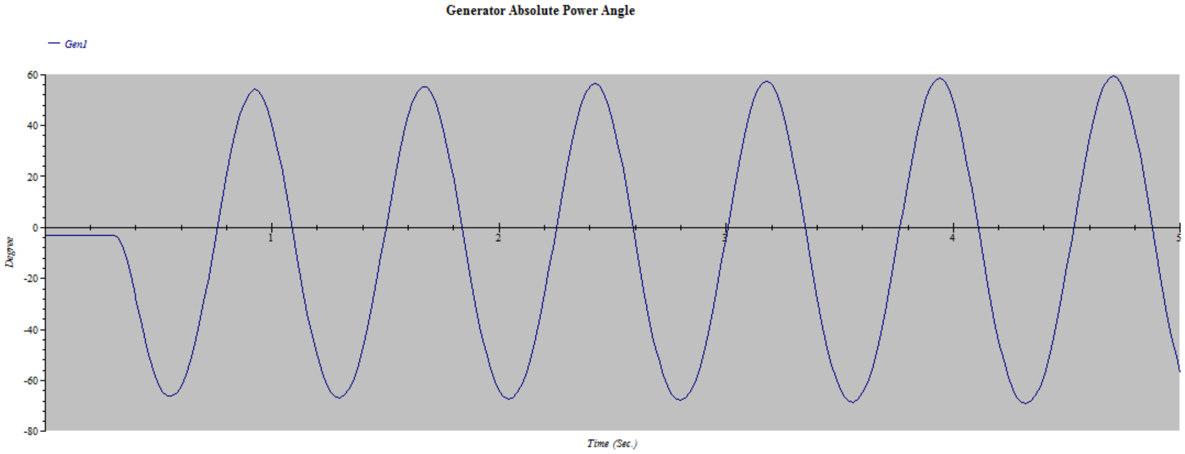


Figure 5.9: Absolute power angle of 100kVA load

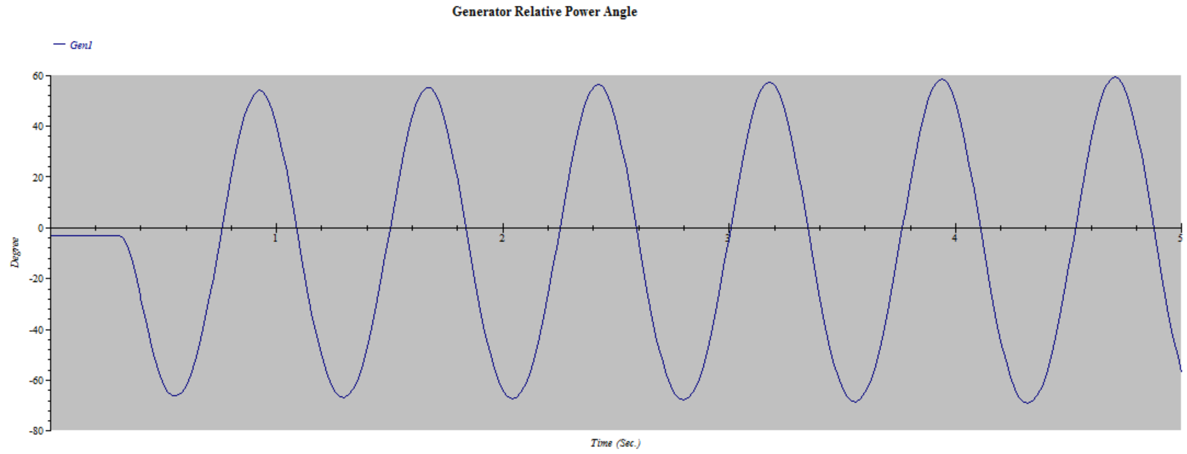


Figure 5.10: Generator relative power angle at 100kVA load

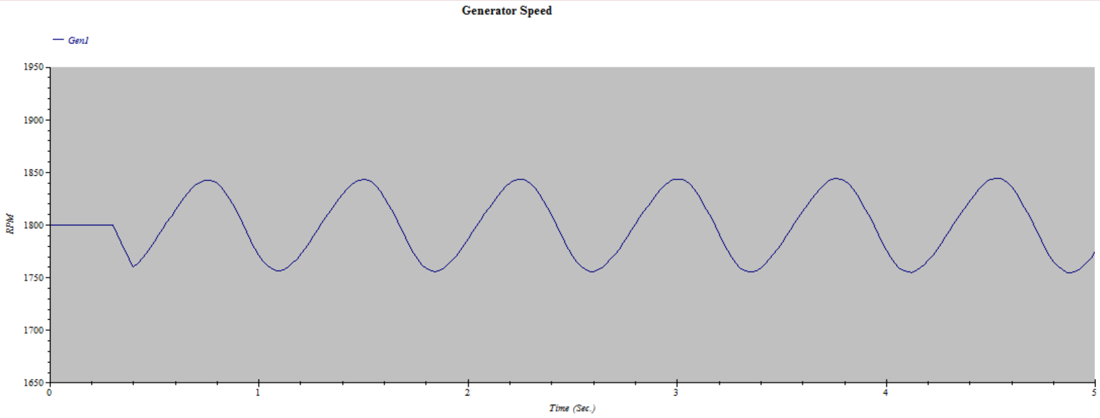


Figure 5.11: Generator speed at 100kVA load

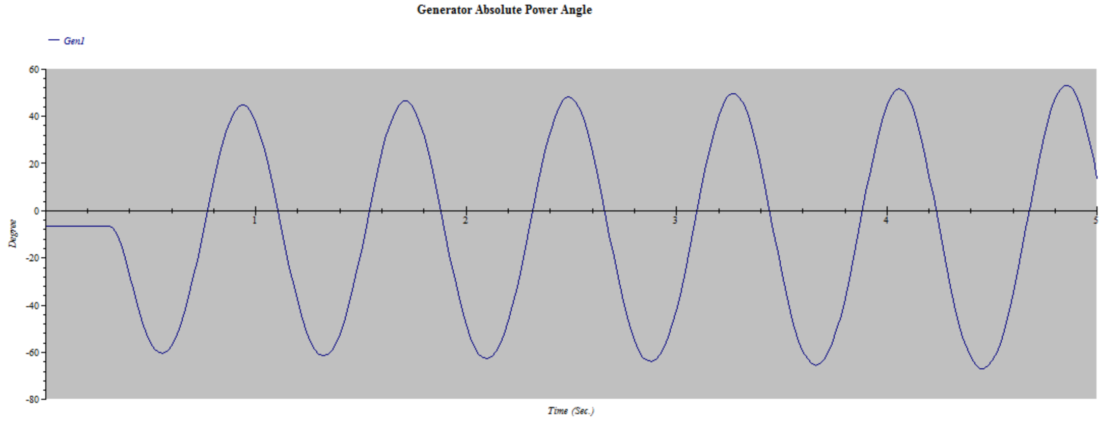


Figure 5.12: Absolute power angle of 200kVA load

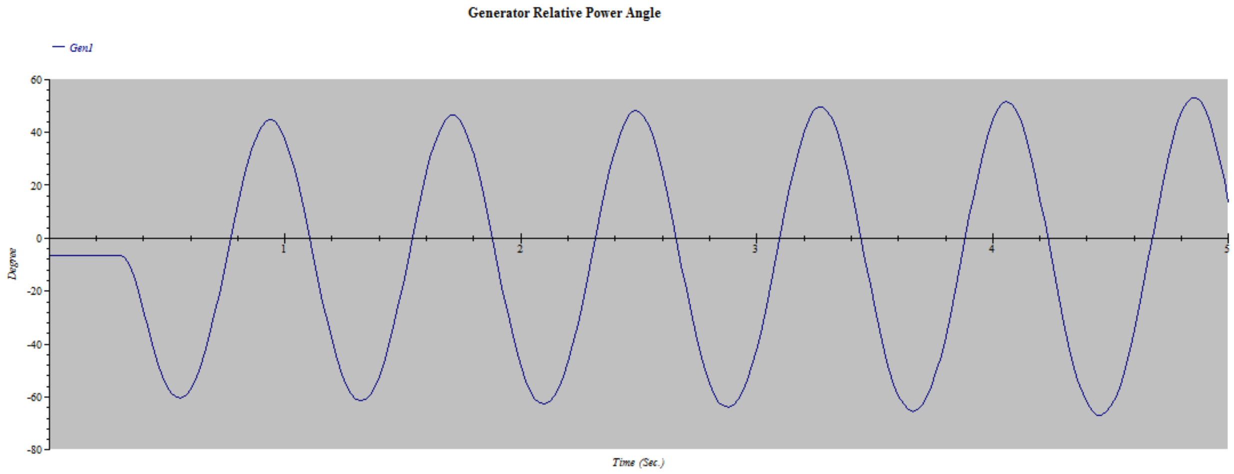


Figure 5.13: Generator relative power angle of 200kVA load

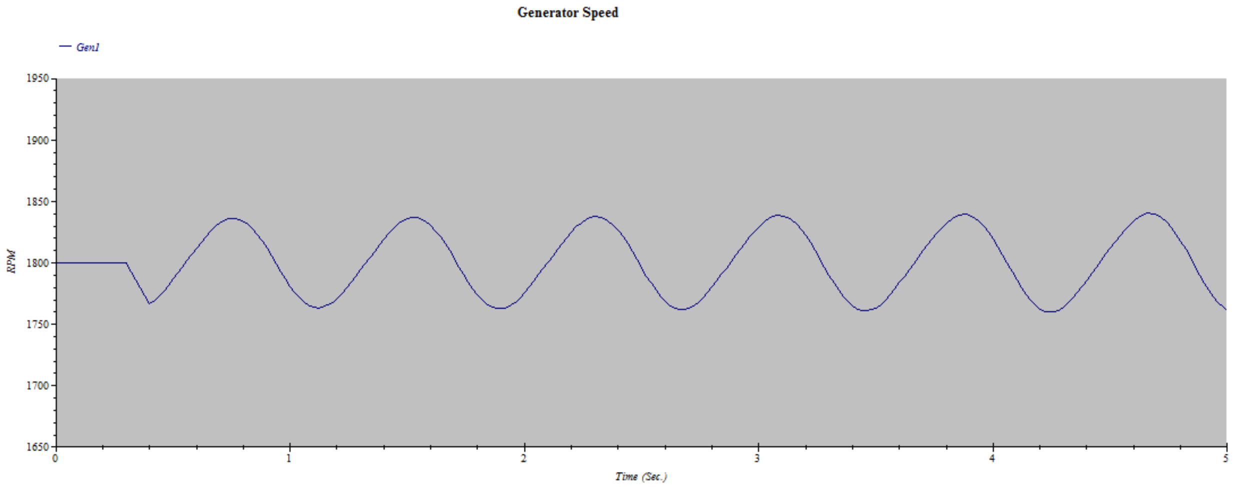


Figure 5.14: Generator speed of 200kVA load

Chapter 6

Conclusion

Having successfully analyzed/solved a conventional load flow with an integrated Photovoltaic in the system the effects were observed.

During pre-fault condition at a load of 100kVA, the system recorded a voltage drop of 3.7% at bus 2. Real power dropped by 1kw, whereas the reactive power dropped by 4kvar. Bus 3 has a voltage drop of 6.88% and loss of 2 kw and 3 kvar. Frequency remains constant and the generator was angle was at -3 deg.

During fault condition at a load of 100kVA, the system recorded a voltage drop of 16.06% at bus 1 while at bus 2, the voltage was dropped to 0%. Real power and reactive power were dropped significantly. And bus 3 has a voltage drop of 63.2%. the system frequency fluctuates and the generator speed also fluctuates.

After fault condition at a load of 100kVA, the system drops were recorded as the voltage at bus 1 was dropped by 0.01% while at bus 2 was dropped by 4.2%. Real power and reactive power increased. Bus 3 has a voltage drop of 8.66% and a drop of 26kw and 7kvar was recorded for the real and reactive power respectively. Similar stability was also recorded when the load was varied with changes according to the demand.

The results analyzed and simulated by the software ETAP 12.6.0, showed that the system voltages are affected by the occurrence of a fault and also whenever the load was increased, the system power angle also widen up. The voltages at different bus terminal are also affected by fault or load variance. The real and reactive power also varies.

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