

POWER SYSTEM TRANSIENT STABILITY STUDY AND ENHANCEMENT OF INDUSTRIAL COGENERATION SYSTEM

(A Case Study at Wonji/showa sugar Factory)

BY: HIWOT H/MARIAM



**A Thesis Submitted to
Adama Science and Technology University
The department of Electrical and Computer Engineering**

**School of Electrical Engineering and Computing
Presented in Partial Fulfillment of the Requirement for the Degree of Master's in
Electrical Engineering (Power system Engineering)**

**Office of Graduate Studies
Adama Science and Technology University**

**Adama
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Advisor(s)

Dr . Kemal Ebrahim



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APPROVAL BY BOARD OF EXAMINERS

We, the undersigned, members of the Board of Examiners of the final open defense by _____ have read and evaluated his/her thesis entitled “POWER SYSTEM TRANSIENT STABILITY STUDY AND ENHANCEMENT OF INDUSTRIAL COGENERATION SYSTEM (Case study at Wonji /Showa sugar factory)” and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master’s in Electrical Engineering (Power system Engineering).

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DECLARATION

I hereby declare that this MSc Thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis/ dissertation have been duly acknowledged.

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To: Electrical And Computer Engineering department

Subject: Thesis/Dissertation Submission

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Signature

Date

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LIST OF ACRONYMS AND ABBREVIATION

AVR	Automatic Voltage Regulator
CHP	Combined Heat and Power
EAC	Equal Area Criteria
EEP	Ethiopian Electric Power
HT-PCC	High Tension Power Control Center
OMIB	One Machine Infinite Bus
SFR	System Frequency Response
TCD	Tone Cane crushed per Day
WSSF	Wonji Showa Sugar Factory
CCT	Critical Clearing Time
MMF	Magneto Motive Force
Te	Electrical Torque
Tm	Mechanical Torque
ETAP	Electrical Transient Analyzer Program

ABSTRACT

Service continuity of the electrical supply is a subject of utmost importance for an industrial cogeneration system. In order to achieve this goal the cogeneration system is tied to a bulk power supply to cover the power mismatch that occur between load and generation, but this also introduces stability problem .This research presents transient stability study and enhancement of industrial cogeneration system of Wonji-Showa Sugar Factory (WSSF)by tie line tripping at the CCT and under frequency load shedding .The system was modeled as One Machine Infinite Bus (OMIB) model and analyzed by a combination of time domain analysis and equal area criteria methods by MATLAB software in addition by selecting the total load , in plant generation and rate of change of frequency the minimum amount of load shedding is determined to maintain load and generation equilibrium and ensure continuity of power supply to the critical loads of the factory. finally the industrial cogeneration plant with its tie line is simulated on ETAP software to verify the accuracy of the determined CCT for successful transition from interconnection mode to islanding and the load shedding scheme by considering various contingencies and load generation. It is concluded that the WSSF power system transient stability can be enhanced by proper design of protective scheme.

Key words:-Transient stability,cogeneration,WSSF,OMIB,CCT,Load shedding, Matlab,ETAP.

CHAPTER ONE

1.INTRODUCTION

1.1. Background

As industrial and commercial operation processes and plants have become more complex and extensive the requirement for improved reliability of electrical power supplies has also increased. The potential costs of outage time following a failure of the power supply to a plant have risen dramatically as well. The introduction of automation techniques into industry and commerce has naturally led to a demand for the deployment of more power system automation, to improve reliability and efficiency. As a result many industrial plants have their own generation installed, Sometimes it is for emergency use only, feeding a limited number of bus bars and with limited capacity. This arrangement is often adopted to ensure safe shutdown of process plant and personnel safety. In other plants, the nature of the process allows production of a substantial quantity of electricity, perhaps allowing export of any surplus to the public supply system at either at sub transmission or distribution voltage levels.

Power supply to critical process loads is extremely important for an industrial cogeneration power plant like WSSF not only for continuous production but also important for overall plant safety during severe disturbances. A sudden interruption of production may result in significant economic loss and raise safety concern. Most of the industrial customers with requirement of uninterrupted input of energy in the form of electric power and steam have installed cogeneration units. The cogeneration systems are broadly defined as the coincident or simultaneous generation of the combined heat and power (CHP) [1].

Co means together, Generation means electrical energy. When steam (in the case of steam turbine) or gas (in the case of gas turbine) expands through the turbine, nearly 60 to 70% of the input energy escapes with the exhaust steam or gas. If this energy in the exhaust steam or gas is utilized for meeting the process heat requirements, the efficiency of utilization of the fuel increases. Such an application, where the electrical power and process heat requirements are met from the fuel, is termed "Cogeneration". Most of the industries need both heat and electrical energy. Hence, cogeneration can be a good investment for industries. Cogeneration system may be based on any type of fuel or heat source and with commercially available technology.

By installing cogeneration units industrial customer can achieve better efficiency of energy usage and enhance the reliability of electricity power supply [2]. The cogeneration has to be tied together with the grid power supply to cover the mismatch of load demand and power output by the cogeneration units in the plant and for the consideration of power quality. Several techno-economic studies [3-5] are required periodically throughout the operating life of the plant to ensure that a cogeneration plant will operate safely, reliably, and economically. To prevent total blackout and to stabilize the system under any abnormal condition, appropriate Islanding and Load Shedding (LS) strategies must be developed for industrial cogeneration system. In this research wonji /showa sugar factory is selected as case study due to the fact that the factory is one of the most important sectors of developing industry in our country as well as its a pioneer in cogeneration plant and exporting power to national grid. This being said the need of power service quality and reliability are much higher than those of general customers .

1.2 Over view of wonji/ showa sugar factory

The Sugar sector is one of the major energy intensive industries while playing an important role in the economy of a country. Presently there are 4 operating factories which are established under the Ethiopian sugar corporation among them the pioneer is wonji /showa sugar factory. Generally the development of sugar industry in Ethiopia is attached to the establishment of Wonji sugar factory which started production in March 1954 and produced 26614 quintals cane sugar during its first campaign.

According to Ethiopian trade and Economic review of 1967, 1968, the Wonji plain lies downstream of the koka dam at an altitude of approximately 1505 meter. It is round on the direction of south east at a distance of 110km from Addis Ababa. Wonji/showa suger factory has currently an installed capacity of 6250TCD sugar production with a 31.15MW power generating capacity.

Unit operations in the factory

The factories operation is divided into factory operation and plantation ,the plantation sector is concerned with the growing of the sugar cane plant while the factory operation is for processing the sugarcane and producing sugar .The factory generally has five plants which are

- cane preparation and milling (Juice extraction plant)

- clarification plant
- boiling plant
- steam and power generation plant(power house)
- water treatment plant and awash pump station

Cane preparation and milling(Juice extraction plant)

The sugar cane that is brought from the fields or cane yard needs to be chopped and fibrized before it enters the mills for juice extraction the main purpose of the plant is to extract the juice from the cane and send the end product of the cane which is called baggase to boiler plant.

Clarification plant

This plant is responsible for clarifying the juice or removing the unwanted dirt from the juice and reducing the viscosity of the juice and converting it to syrup which has a higher bricks than the juice by the form of boiling by vessels called evaporators.

Boiling house

This plant is found next to the evaporation or clarification plant with its hole function being actually making the sugar it contains pans for boiling centrifugal machines for curing the masscutes and producing white sugar as well as packaging and transferring it to storing facility.

Steam and power generation plant

This plant consists of all the cogeneration facilities which are the boiler and all its necessary facilities for producing steam ,turbine ,alternator and power generation distribution and all the necessary switch gears facilities

Water treatment plant

This plant is responsible for pumping water required for the factory from awash river and delivering clarified and treated water to the boiler as well as water required for the factory operation .It consists of pump station and water treatment facilities.

1.3 WSSF power System description

The cogeneration system for this study is built in Wonji/showa sugar factory. WSSF cogeneration plant has built One 31.25MW steam turbine driven generator and two diesel generator with a capacity of 625kva and 1250kva. Single line diagram of the system is shown

Both Grid and the cogeneration facility paralleled together supply power to total factory load. Both the alternator and grid incoming cables are connected on 11KV bus bar in the power house and from there they supply the other loads .

The loads connected to the bus are Transformer 1 and Auxiliary Transformer one supplying the power house and boiler auxiliaries as well as lighting and socket groups, Transformer 2 supplying clarification plant and water treatment plant, Transformer 3 supplying Boiling plant, Mill house HT panel which supplies mill house mill, 11kv fibrizer supply, Awash pump station overhead line, Earthing transformer and DG incomers.

Generally according to the design turbo-alternator should be suitable to meet demands imposed during different operating modes of the Co-generation plant. The modes are classified in 3 different categories as listed below.

Mode A: Factory “ON” & Grid “ON”

When co-generation plant and grid are running in parallel. This is the mode for normal operation. Factory shall be operating in this mode for about 4398 hrs in a year.

power available at the alternator terminal=31.25MW

Mode B: Factory “OFF” & Grid “ON”

When factory is not working, but turbo-alternator is running to export power to grid. Factory shall be operating in this mode for about 776 hrs in a year. power available at the alternator terminal=27.2 MW

Mode C: Factory “ON” & Grid “OFF”

When factory is operating but grid is off due to some reason. Turbo-alternator shall be running at reduced load during this mode, Factory shall be operating in this mode for about 89.8 hrs in a year.

power available at the alternator terminal=10.40MW

1.4 Statement of the problem

Wonji/ showa sugar factory is a factory found in the northern Adama with a capacity of 6250 TCD with a cogeneration plant 31.25 MW installed capacity of generator. The factory generates power for its internal use and export the surplus power to the national grid. Even though the factory is generating its own power ;since it is connected to the grid system the disturbances that occur on its tie line directly affect its power system .

One of the main problem that is observed in wonji /showa factory cogeneration plant is that even though the cogeneration system has a correct configuration for reliable operation as shown on fig1 the power system control and protection system does not provide the reliability

level that is intended. When a fault occurs in the EEP grid or a transmission line connecting the WSSF power plant to the grid, a total black out occurs in the factory .In other words when a fault occurs on the EEP grid instead of tripping the tie line breaker and islanding the cogeneration plant and performing load shedding if necessary ,the system simply trips the turbo generator and the tie line all together. A table showing data collected from the factory log book on causes of the generator tripping in the factory operation season of 2016/18 is shown on the Appendix.

As sugar manufacturing industries require uninterrupted supply of power in the form of heat (steam) and electricity through out there production season , unplanned interruption of power to the factories causes shut down of the process, loss in batch of the production as well as may create a dangerous condition if the situation is not mitigated fast.

According to the WSSF operation log book records restarting of plants like boiler up to continuing of the crushing require 1 - 3 hrs depending the length of power outage. The factory produces 6250 quintals of sugar per day or 260 quintal per hr when working in its capacity ,with in a 3 hrs down time the factory losses 781.4 quintals of production, when this is converted into currency 10,93960 birr .This is excluding the time that is taken to solve the actual problem that occurred on the power system since it depends on the kind of fault that has happened.

According to IEEE 0493-2007 and Considering the above listed facts in this research the system transient stability is analyzed in detail and appropriate fault clearing time of sending end tie line breakers are determined by using a simple approach for increasing the system reliability. ETAP and MATLAB are used as a main simulation tools.

1.5 Objective

1.5.1 General Objective

- The main objective of this thesis work is to enhance the power system transient stability of the WSSF power system by investigating the factories power system with its tie line and determining the critical clearing time for the circuit breakers for islanding of the system and providing load shedding schemes for emergency situation.

1.5.2 Specific objective

The specific objectives of this study include:

- To determine critical clearing times for circuit breaker for transferring the system from interconnected mode to islanded system in the events stability endangering fault.
- To analyze the situation of sudden single phase and three-phase fault on transmission line via the equal area criterion method, whether the system may cause the system instability and its stability margin and provide appropriate load shedding schemes for emergency situation .

1.6 Significance of the thesis

- This thesis will be useful for solving the problem of unwanted power interruption that could be avoided by proper setting of protection equipments that are already installed in the factory premises.
- This study could serve as a base study for other sugar factories that has cogeneration plants and encourage them to examine their system and get the full potential of cogen plants

1.7 Scope of the study

The study of transient stability is very vast and covers a wide area of subjects but this study is limited to only transient stability assessment of wonji /showa sugar factory power system for enhancing the system response in the event of faults and the results obtained on the analysis are only for decoupling scheme and load shedding and are applicable only to factories protection system.

CHAPTER TWO

2.LITRETURE REVIEW

2.1 Theory Related to Transient Stability

2.1.1 Stability

The stability of a system refers to the ability of a system to return back to its steady state when subjected to a disturbance. Power is generated by synchronous generators that operate in synchronism with the rest of the system. A generator is synchronized with a bus when both of them have same frequency, voltage and phase sequence. Usually power system stability is categorized into Steady State, Transient and Dynamic Stability [3].

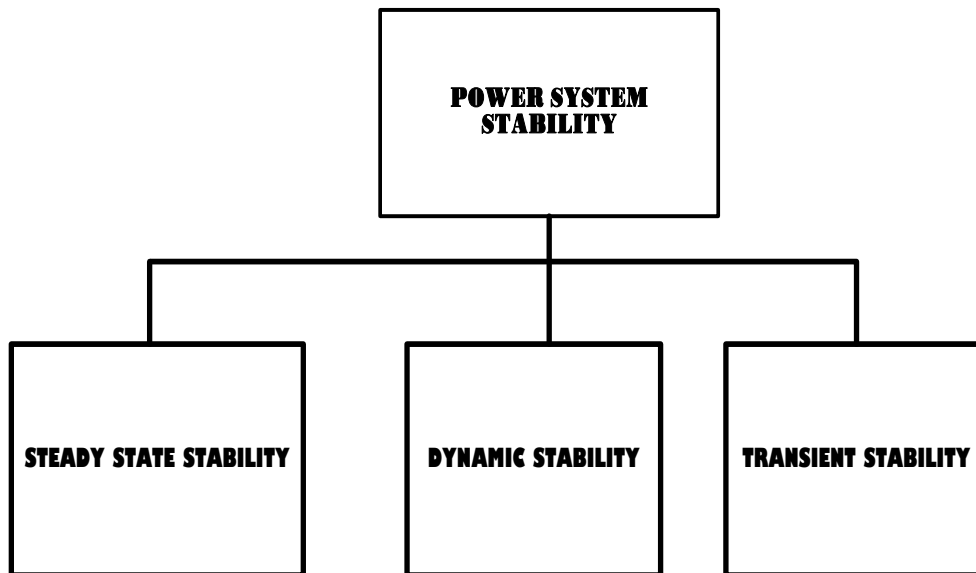


Fig 2.1 categories of power system stability

2.1.2 Steady State Stability

Steady state stability is the ability of the system to develop restoring forces equal to or greater than the disturbing force and remain in equilibrium or synchronism after small and slow disturbances. Increase in load is a kind of disturbance. If increase in loading takes place gradually and in small steps and the system withstands this change and performs satisfactorily, then the system is said to be in steady state stability. Thus the study of steady state stability is

basically concerned with the determination of upper limit of machine's loading before losing synchronism, provided the loading is increased gradually at a slow rate. In practice, load change may not be gradual. Further, there may be sudden disturbances due to

- i) Sudden change of load
- ii) Switching operation
- iii) Loss of generation
- iv) Fault

2.1.3 Dynamic Stability

Dynamic stability is the ability of the power system to maintain stability under continuous small disturbances also known as small-signal stability. These small disturbances occur due random fluctuations in loads and generation levels. Furthermore this stability is able to regain synchronism with inclusion of automatic control devices such as automatic voltage regulator (AVR) and frequency controls. This is the extension of the steady state stability which takes a longer time to clear the disturbances [5].

2.1.4 Transient Stability

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as the occurrence of a fault, the sudden outage of a line or the sudden application or removal of loads [3]. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship. Following such sudden disturbances in the power system, rotor angular differences, rotor speeds, and power transfer undergo fast changes whose magnitudes are dependent upon the severity of disturbances. For a large disturbance, changes in angular differences may be so large as to cause the machine to fall out of step. This type of instability is known as Transient Instability. Transient stability is a fast phenomenon, usually occurring within one second for a generator close to the cause of disturbance. The objective of the transient stability study is to ascertain whether the load angle returns to a steady value following the clearance of the disturbance [6].

Each generator operates at the same synchronous speed and frequency of 50 hertz while a delicate balance between the input mechanical power and output electrical power is maintained. Whenever generation is less than the actual consumer load, the system frequency falls. On the other hand, whenever the generation is more than the actual load, the system frequency rise. The generators are also interconnected with each other and with the loads they supply via high voltage transmission line [7].

Any disturbance in the system will cause the imbalance between the mechanical power input to the generator and electrical power output of the generator to be affected. As a result, some of the generators will tend to speed up and some will tend to slow down. If, for a particular generator, this tendency is too great, it will no longer remain in synchronism with the rest of the system and will be automatically disconnected from the system. This phenomenon is referred to as a generator going out of step

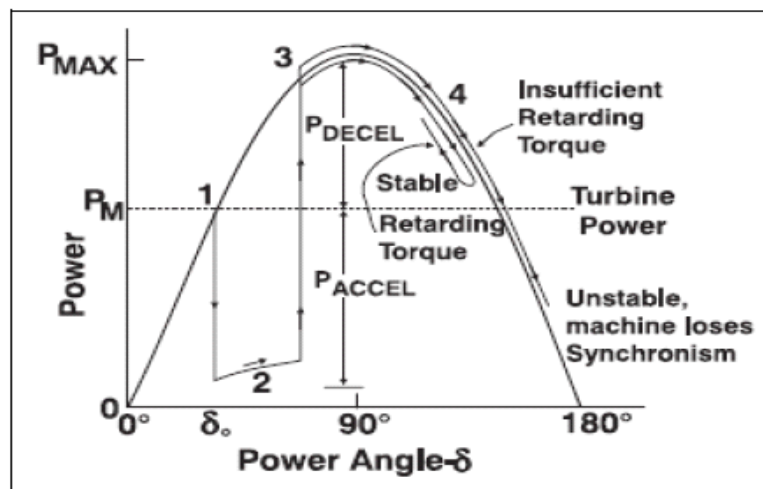


Fig 2.2 transient stability illustration[6]

Transient stability is primarily concerned with the immediate effects of a transmission line disturbance on generator synchronism. Figure 2.2 illustrates the typical behavior of a generator in response to a fault condition. Starting from the initial operating condition (point 1), a close-in transmission fault causes the generator electrical output power to be drastically reduced. The resultant difference between electrical power and the mechanical turbine power causes the generator rotor to accelerate with respect to the system, increasing the power angle (point 2).

When the fault is cleared, the electrical power is restored to a level corresponding to the appropriate point on the power angle curve (point 3). Clearing the fault necessarily removes one or more transmission elements from service and at least temporarily weakens the transmission system. After clearing the fault, the electrical power output of the generator becomes greater than the turbine power, this causes the unit to decelerate (point 4), reducing the momentum the rotor gained during the fault. If there is enough retarding torque after fault clearing to make up for the acceleration during the fault, the generator will be transiently stable on the first swing and will move back toward its operating point. If the retarding torque is insufficient, the power angle will continue to increase until synchronism with the power system is lost [7].

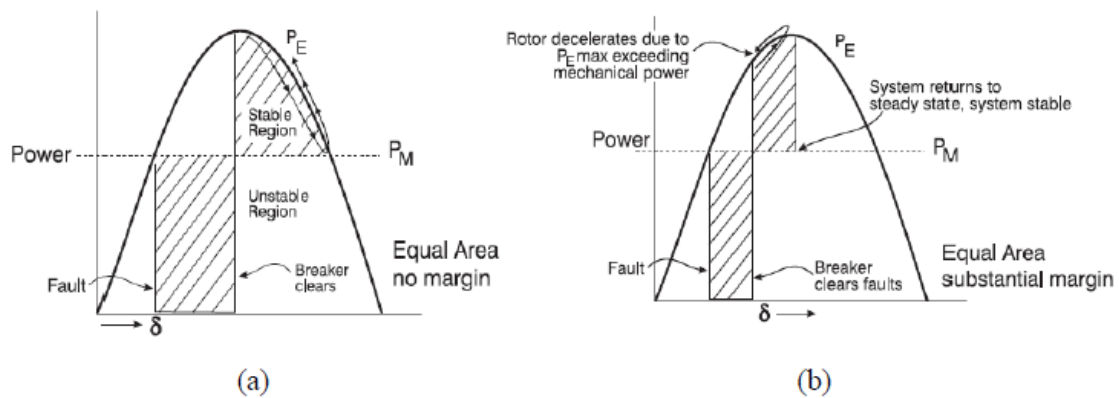


Fig 2.3 (a and b) transient stability with different stability margins[6]

Power system stability depends on the clearing time for a fault on the transmission system. Comparing the two examples in figure 2.3 illustrates this point. In the example of slower fault clearing in figure 2.3 (a), the time duration of the fault allows the rotor to accelerate so far along the curve of P_E that the decelerating torque comes right to the limit of maintaining the rotor in synchronism. The shorter fault clearing time in figure 2.3 (b) stops the acceleration of the rotor much sooner, assuring that sufficient synchronizing torque is available to recover with a large safety margin. This effect is the demand placed on protection engineers to install the fastest available relaying equipment to protect the transmission system [7].

2.1.5 Swing Equation

Under normal operating condition, the relative position of the rotor axis and the resultant magnetic field axis is fixed. The angle between the two is known as the power angle or torque angle. During the disturbance, rotor will decelerate or accelerate with respect to the synchronism rotating air gap MMF, and the relative motion begins. If the oscillation, the rotor locks back into synchronism speed after the oscillation, the generator will maintain its stability. If the disturbance does not involve any net changes in the power, the rotor returns to its original position. If the disturbance is created by a changes in generation, load, or in network conditions, the rotor comes to a new operating power. The acceleration power P_a and the rotor angle δ is known as Swing Equation. Solution of swing equation will show how the rotor angle changes with respect to time following a disturbance. The plot of δ vs time t is called the Swing Curve. Once the swing curve is known, the stability of the system can be assessed. angle relative to the synchronously revolving field.

Consider a synchronous generator developing an electromagnetic torque T_e It receives mechanical power P_m at the shaft torque T_m and running at the synchronous speed, via shaft from the prime-mover. It delivers electrical power P_e to the power system network via the bus bars. If T_m is the driving mechanical torque, and then under steady-state operation with losses neglected we have

$$T_e = T_m \quad \text{Eq(2.1)}$$

Due to a disturbance, an acceleration ($T_m > T_e$) or decelerating ($T_m < T_e$) torque on a rotor is produced,

If J is the combined moment of inertia of the prime mover and generator, neglecting frictional and damping torque, the swing equation is represented by

Swing equation in terms of inertia constant M ,

$$M \frac{d^2 \delta}{dt^2} = p_m - p_e \quad \text{eq(2.2)}$$

converting it to per unit

$$\frac{2H}{\omega_s} * \frac{d^2 \delta}{dt^2} = p_m(\text{pu}) - p_e(\text{pu}) \quad \text{eq(2.3)}$$

where M =inertia constant

δ =rotor angle

P_m =mechanical power

P_e =electrical power

Swing curve, which is the plot of torque angle δ vs time t , can be obtained by solving the swing equation. These curves are used to determine the stability of the system. If the rotor angle δ reaches a maximum and then decreases, then it shows that the system has transient stability. On the other hand if the rotor angle δ increases indefinitely, then it shows that the system is unstable.[12]

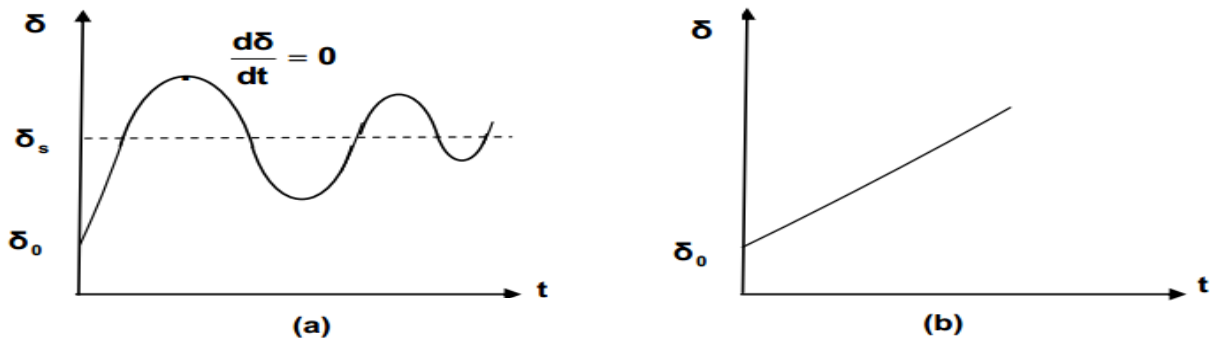


Fig 2.4 stable (a) and unstable (b) swing curves

2.1.6 Equal area criteria

The transient stability studies involve the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbance. This may be sudden application of load, loss of generation, loss of large load, or a fault on the system. In most disturbances, oscillations are of such magnitude that linearization is not permissible and the nonlinear swing equation must be solved. A method known as the equal-area criterion can be used for a quick prediction of stability. This method is based on the graphical interpretation of the energy stored in the rotating mass as an aid to determine if the machine maintains its stability after a disturbance. The method is only applicable to a one-machine system connected to an infinite bus or a two-machine system [7]. From the swing equation

$$\frac{M d^2 \delta}{dt^2} = p_m - p_e \quad \text{eq(2.5)}$$

From eq (2.5)

$$\frac{d^2\delta}{dt^2} = \frac{1}{M}(P_m - P_e)$$

multiplying by $2\frac{d\delta}{dt}$ and integrating both sides

$$\left(\frac{d\delta}{dt}\right)^2 = \frac{2}{M} \int (P_m - P_e)d\delta \quad \text{eq(2.6)}$$

$$\frac{d\delta}{dt} = \sqrt{\frac{2}{M} \int (P_m - P_e)d\delta} \quad \text{eq(2.7)}$$

Equation (2.7) gives the relative speed of the machine with respect to the synchronously revolving reference frame. For stability, this speed must be zero at the sometime after the disturbance. Therefore the stability criterion,

$$\int_{\delta_0}^{\delta} P_m - P_e d\delta = 0 \quad \text{Eq(2.8)}$$

Consider the machine operating at the equilibrium point δ_0 , corresponding to the mechanical power input $P_{m0}=P_{e0}$ as shown in figure 2.7. Consider a sudden increase in input power represented by a horizontal line P_m . Since $P_m > P_{m0}$, the acceleration power on the rotor is positive and the power angle δ increases. The access energy stored in the rotor during the initial acceleration is,

$$W_{acc} = \frac{2}{M} \int_{\delta_0}^{\delta_1} (P_{m1} - P_e)d\delta \quad \text{eq (2.9)}$$

With increase in δ , the electrical power increases and $\delta = \delta_1$, the electrical power matches the new input power P_{m1} . Even though the accelerating power is zero at this point, the rotor is running above synchronous speed; hence δ and the electrical power P_e continue to increase.

Now , $P_m < P_e$ causing the rotor decelerates toward synchronous speed until $\delta = \delta_{\max}$. The energy given as the rotor decelerates back to synchronous speed is,

$$\text{area2} = \text{area bde} = \int_{\delta}^{\delta_{\max}} (P_m - P_e) d\delta \quad \text{eq (2.10)}$$

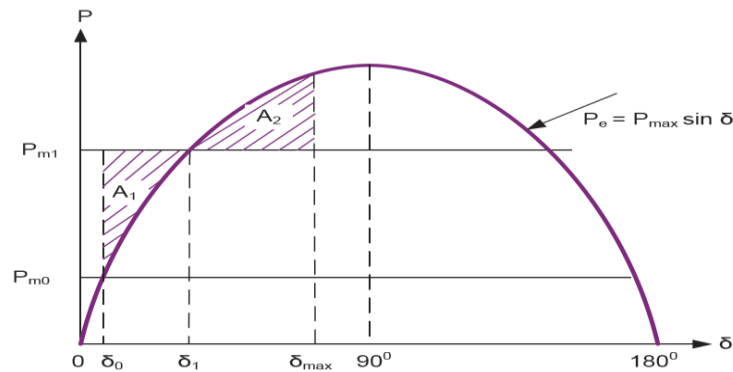


Fig 2.5: Equal area criterion - sudden change of load

The result is that the rotor swings to point b and the angle, at which point

$$\text{area } A_1 = \text{area } A_2$$

This is known as the equal area criterion. The rotor angle would then oscillate back and forth between δ_0 and $\delta_{\max}$ at its natural frequency. The damping present in the machine will cause these oscillations to subside and the new steady state operation would be established at point b.

2.2 Factors influencing transient stability

- i) Generator inertia
- ii) Generator loading
- iii) Generator output (power transfer) during fault- depends on fault location and fault type
- iv) Fault clearing time
- v) Post-fault transmission system reactance
- vi) Generator reactance

vii) Generator internal voltage magnitude-this depends on field excitation, i.e. the power factor of the power sent at the generator terminals

viii) Infinite bus voltage magnitude.

2.3 Causes of Transient in cogeneration plants

Transients are disturbances that occur for a very short duration and the electrical circuit is quickly restored to original operation provided no damage has occurred due to the transient. An electrical transient is a cause-and-effect phenomenon. For transients to occur there must be a cause, some of the more common causes of transients:

i) Atmospheric phenomena (lightning, solar flares, geomagnetic disturbances)

ii) Switching loads on or off

iii) Interruption of fault currents

iv) Switching of power lines

v) Switching of capacitor bank

2.4 Transient stability analysis of industrial cogeneration plant

If a power system of an industrial facility is exposed to external disturbances and it reach a new acceptable operating condition after the disturbance has been removed. This property of the power systems is usually known as “Power System Stability” (with on-site generation connected to the utility grid, should be able to withstand severe transient) [6]. As mentioned before, dynamical studies, i.e., transient stability, are hardly performed on industrial power systems [10].

Transient stability studies are fundamental for both understanding the transient behavior of the electrical power system and determining the nature of corrective measures to be implemented with the aim of ameliorating the system performance following the occurrence of a major disturbance, determination of fault critical clearing time and designing of load shedding schemes are some examples of corrective measures based on transient stability studies. Therefore, this type of studies should be carried out in industrial power systems if, on-site generation exists or is planned, synchronous motors are an important portion of the system

load, the industrial-utility tie is lost, disturbances on the utility grid causes plant shutdown [9]. In general, transient stability of a power system may be defined as the ability of the system to remain in synchronism when subjected to a severe transient disturbance [6]. This ability is greatly affected by both the initial system operating condition and the magnitude of the disturbance. The resulting system response is influenced by the non-linear power–angle relationship and it is characterized by large excursions of the generator rotor angles.

[13] published a paper in 2010 on the transient stability analysis of an industrial cogeneration system in the Science Park housing a segment of the semiconductor industry in Taiwan. They point out that the importance of the semiconductor industry leads to a much higher requirement for power service quality and reliability than for general customers. Therefore, keeping the reliability and stability of power service for the Science Park becomes quite an important issue. The cogeneration in the Science Park consists of three gas turbines and one steam turbine, with a total capacity much more than WSSF. The authors describe various operating scenarios, and note that a load shedding scheme is implemented when the generated power is less than the internal load, in order to avoid a plant blackout during the islanding mode of operation.

[9] performed a simulation of a large electrical power system using ETAP software. Based on the outcomes, analysis and monitoring can be conducted on over-loading of power/distribution transformers, line conductor and cable current carrying ability, power factors, supply demand gaps, voltage drops, transmission losses, active and reactive powers, voltage and current magnitudes, as well as total Harmonic Distortion in voltage and current. The complete power system can be simulated, and utilities can integrate divergent grids as they are actually connected using this approach. An additional benefit is that utilities can use this simulation in their planning.

[8] analyzed an industrial plant with a 62 MW load. The plant also had four 10 MW cogeneration units which provided steam to the plant and generated 27 MW of power. The remaining 35 MW of load had to be supplied by the grid. A condensing type cogeneration unit with 40 MW capacity was added to the system in 1998 [8]. Due to disturbances on the bulk power system, they were concerned with coordination of the tie line protection and the setting of load shedding relays in order to maintain the supply of crucial loads in the industrial plant.

Transient stability simulations are usually performed using time domain simulation methods, and the mathematical model of the power system is described by one set of differential equations and another of algebraic equations, and the software tools for solving those sets of equations are based on step-by-step numerical integration [6]. In the case of industrial power systems, transient stability studies are mainly focused to assess and implement cost effective measures with the aim of reducing the risk of shutdowns of the industrial complex due to a sudden loss of a large amount of local generation or load, or to the loss of the industrial-utility tie and the starting of large induction motors direct-on-line .

2.5. Transient stability analysis method

There are several methods to study the transient stability of Electric Power Systems. These methods can be gathered in four groups: Numerical Integration Methods, Direct Methods, Hybrid Methods and Artificial Intelligence Technique.

2.5.1 Numerical Integration Methods

An Electric Power System can be described by two sets of equations: a differential set related to the generators and an algebraic set related to the others components [3]. The way these methods study the transient stability of the system is solving, in the time, the two sets of equations mentioned above.

The transient stability analysis requires the solution of a system of coupled non-linear differential equations. In general, no analytical solution of these equations exists. However, techniques are available to obtain an approximate solution of such differential equations by numerical methods and one must therefore resort to numerical computation techniques commonly known as digital simulation. Some of the commonly used numerical techniques for the solution of the swing equation are:

- Euler modified method
- Runga – Kutta method
- Point by point method

2.5.2 Direct Methods

These methods are also called Energy Function Methods, because they are based in comparisons of energy values [5]. More precisely, these methods calculate the energy value at the clearing time and the critical energy value. If the energy value at the clearing time is higher than the critical energy value the system is unstable, otherwise the system is stable. These methods only require to solve the equations during the fault period, which leads to lower computation times. This method uses the famous equal area criteria.

2.5.3. Hybrid Methods

The Hybrid Methods gather the advantages from the Numerical Integration Methods with the advantages from the Direct Methods [3]. From the first they get the modeling capabilities, whereas from the second they get the fast analysis capabilities.

2.5.4 Artificial Intelligence Techniques

These are the newer approach to assess the transient stability of Electric Power Systems [3]. Unlike the previous methods, which are all deterministic, these kind of methods are probabilistic. They are characterized by being necessary to do a lot of simulations before being ready to use. However, when in use, they provide a very fast analysis.

2.5.5 Comparison between Methods

Between all the methods presented here, the best results are obtained with the Hybrid Methods and with the Artificial Intelligence Techniques. Due to the simulations that the Artificial Intelligence Techniques require before being ready to use, the Hybrid Methods take advantage when it's necessary to choose one [3].

CHAPTER THREE

3. METHODS AND MATERIALS

3.1 Data collection and transient stability study

For undergoing the research work data has been collected from many sources; documents, Manuals, interviews, direct observation ,daily and annual records of the factory power generation and consumption logbooks.

3.2 Analysis ,computation and simulation methods of transient stability of WSSF cogeneration system

3.2.1 Mathematical modeling

OMIB (one machine infinite bus) methods rely on the observation that the loss of synchronism of a multi machine power system originates from the irrevocable separation of its machines into two groups, which are replaced by a two machine system and then by an OMIB equivalent. Thus, an OMIB may be viewed as a transformation of the multidimensional multi machine dynamic equations into a single dynamic equation. This latter takes on various forms, depending upon the power system modeling and the assumed behavior of the machines within each group. The foundations of all these OMIBs rely on the classical, well-known equal area criterion (EAC).[11]

A time invariant OMIB is obtained under the following assumptions: (i) simplified power system modeling; (ii) coherency of the machines within each one of the two groups, so as to “freeze” their relative motion in the fault on and the post fault periods.

The case study for this research as described above is cogeneration system consisting of one steam driven generator connected to the national grid(EEP) thus a simplified model of the OMIB model is used for analysis .In this model we write the power flow in the direction defined current flow.

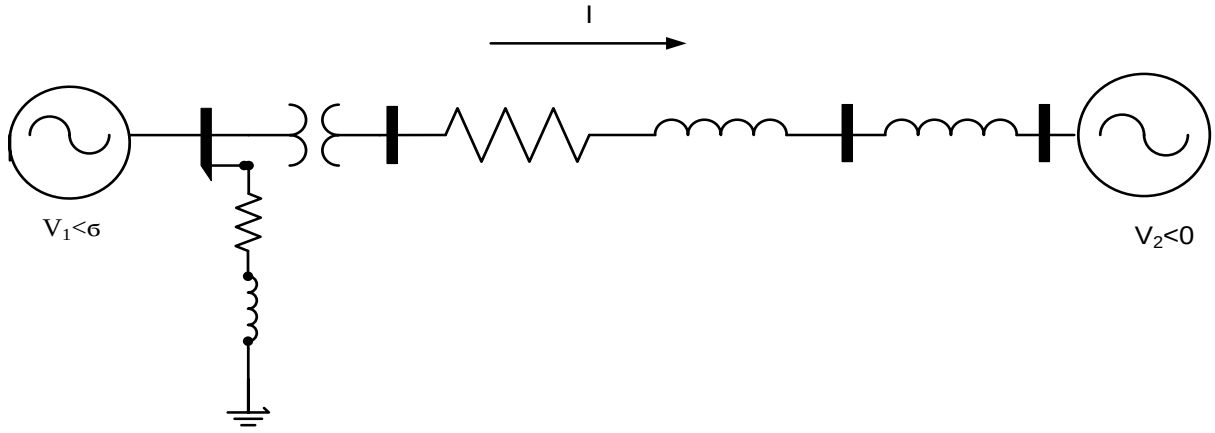


Fig 3.1 OMIB representation

The above system can be modeled as two port network

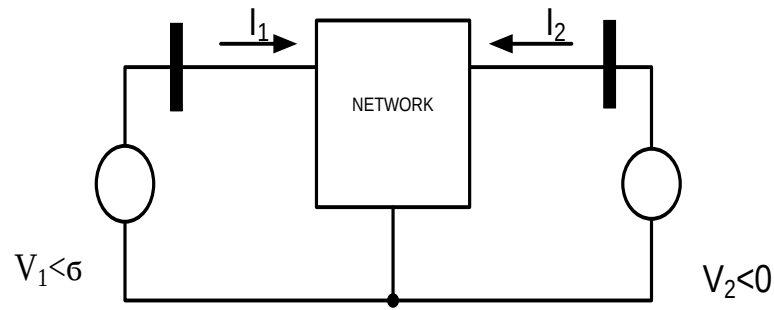


Fig 3.2 Two port network representation of OMIB

with the two port equation

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad \text{eq (3.1)}$$

$$Y_{11} = G_{11} + jB_{11} \quad \text{eq(3.2)}$$

$$Y_{12} = G_{12} + jB_{12} \quad \text{eq(3.3)}$$

The two voltages are defined exactly as before. Since the current leaving Generator 1 is defined by the admittance equation (3.2&3.3), we may again compute the power injected by Generator 1 by solving (3.4), with the result

$$P_1 + jQ_1 = V_1^2(G_{11} - jB_{11}) + V_1V_2[(G_{12}\cos\delta) + j(G_{12}\sin\delta - B_{12}\cos\delta)] \quad \text{eq (3.4)}$$

From this equation we readily compute the power injected by Generator 1 to be

$$P_1 = V^2(G_{11}) + V_1V_2(G_{12}\cos\delta + B_{12}\sin\delta) \quad \text{eq (3.5)}$$

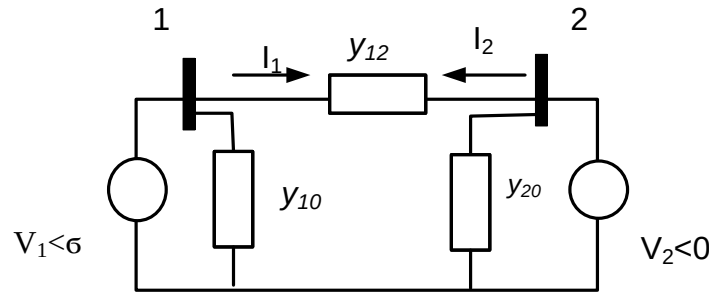


Fig. 3.3 The equivalent two port seen by Generator 1.

Since the network seen by Generator 1 is only a two port, it can be represented immediately by the circuit shown on fig using only two admittances. Any network connecting the two generators can be simplified to this form although it may require Y-D transformation to do so. With the system described in this way we may write the matrix admittances as

$$Y_{11} = y_{10} + y_{12}$$

$$Y_{12} = Y_{21} = -y_{12}$$

$$Y_{22} = y_{12} + y_{20}$$

where the lowercase admittances show actual values where the upper case admittances represent the matrix elements

The electrical power output of each machine can now be expressed in terms of the machine's internal voltages

from eq(3.5) the electrical power

$$P_e(i) = \text{Re}(E_i \cdot I_i) \quad \text{eq (3.6)}$$

$$I_i = \sum E_j \cdot Y_{ij} \quad \text{eq (3.7)}$$

equation (3.6) is the same as power transfer before disturbance, and prior to disturbance there is equilibrium between mechanical power input and electrical power output.

The classical transient stability study is based on the application of a three-phase fault. A solid three-phase fault at bus k in the network results in $V_k = 0$. This is simulated by removing the

kth row and column from the Perrault bus admittance matrix. The new bus admittance matrix is reduced by eliminating all nodes except the internal generator nodes. The generator excitation voltages during the fault and post fault modes are assumed to remain constant. The electrical power of the generator in terms of the new reduced bus admittance matrices are obtained. The equivalent IMIB motion equation

$$M\ddot{\delta} = p_m - p_e$$

The well-known equal-area criterion provides a synthetic transient stability assessment via the stability margin:

$\eta = A_{dec} - A_{ae}$ and states that: for a given stability scenario the OMIB system is unstable (resp. stable) if $\eta < 0$ (resp. $\eta > 0$). The border line case, $\eta = 0$, provides the limit (in)stability condition, in terms of critical clearing time or critical clearing angle.

The general procedure followed for determine the critical clearing angle and critical clearing time

1. Development of mathematical model WSSF power system with its tie line and determining of Pre fault values by load flow analysis, P_e , P_m , sending and receiving end voltages and transfer reactance between the systems is done
2. Simulation of a short circuit at the place of interest on the system and determine the transfer reactance during fault is done
3. The system reactance after the faulted part of the transmission line is isolated is determined.
4. By Apply the equal area criteria determining of critical clearing angle and CCT is done on Matlab .
5. simulation of the swing curve at the critical clearing time to determine the system is stable or not is performed.

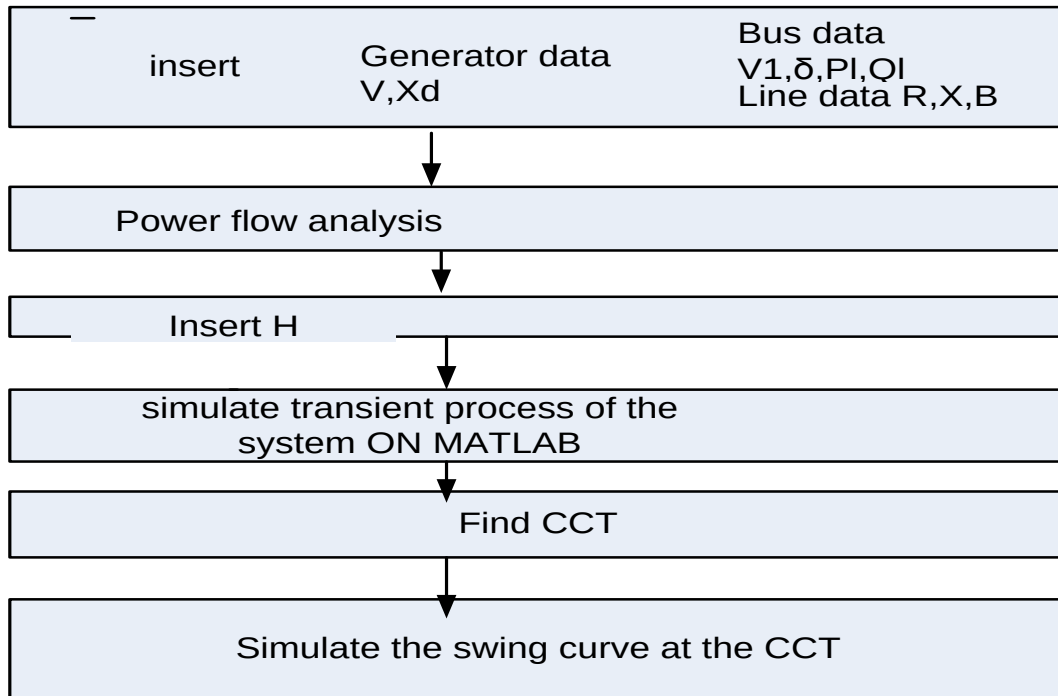


Fig. 3.4 flow chart of transient stability for matlab code

3.3 Transient stability analysis of WSSF system on the event of external faults

Table 3.1 Generator data

Q(KVA)	38937.5
P(KW)	31150
Frequency	50Hz
Voltage	11000
Current	2044A
Power factor=0.8	Short circuit ratio=0.54
Speed=1500min-1	poles=4
Xd%	$1/\text{scr} \times 100 = 1/0.54 \times 100 = 1.865\%$
Synchronous reactance sat/unsat,Xd%	1.865/2.12pu
Direct axis transient reactance(xd')sat/unsat	0.327/0.372pu

Table 3.2 Transmission line data

KM	location	Resistance/km	Total Resistance(ohm)	Reactance/km	Total Reactance(ohm)
5	Sw.y.- Awash Melk. S.S.	0.183	0.915	0.424	2.12
3	Sw.yard- Taping point	0.183	0.462	0.424	1.272
58	Sw.yard- Adama S.S	0.183	10.614	0.424	24.592

Table 3.3 Transformer data

power	30MVA
Voltage HV/LV	132kv/11kv
%Impedance	12%
Fault level	10000MVA for3sec based on its own %Z
SCT	40KA for 3secpo
cooling	ONAF

Using equal area criteria and time domain analysis the stability margin for the generator ,the critical clearing angle ,critical clearing time for the circuit breaker is computed as follows swing equation

$$\frac{2H}{\omega_0} * \frac{d\delta^2}{dt^2} = P_a$$

applying EAC

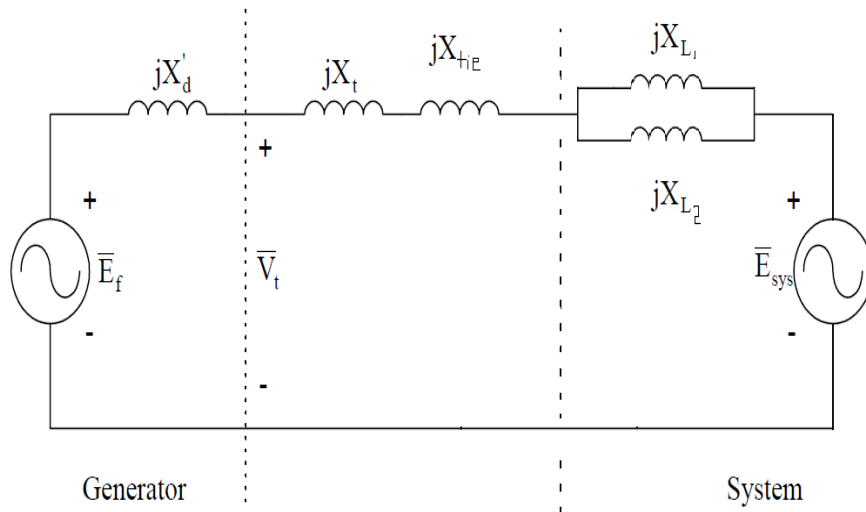


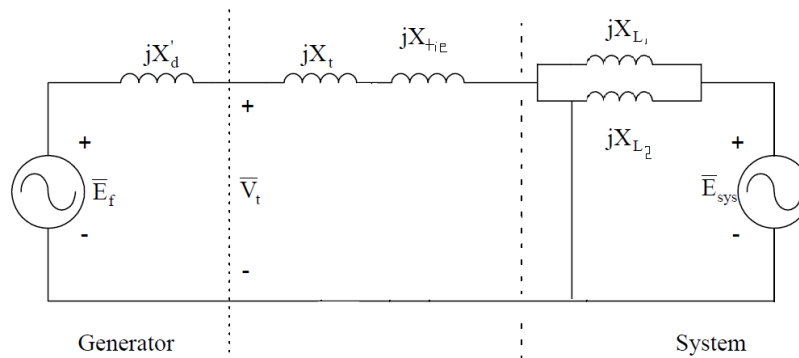
Fig 3.5 OMIB representation of WSSF power system tied with the grid
using 40MVA as base value for all analysis

$$S_b = 40\text{MVA } V_b = 11\text{KV}$$

$$I_b = \frac{S_b}{\sqrt{3} \cdot 11\text{KV}} = \frac{40\text{MVA}}{19.0525} = 2099.45$$

$$Z_b = \frac{V_b}{\frac{I_b}{\sqrt{3}}} = \frac{11\text{KV}/\sqrt{3}}{2099.45} = 3.025$$

3.3.1 Case 1 Single phase to ground short circuit at transmission line 2



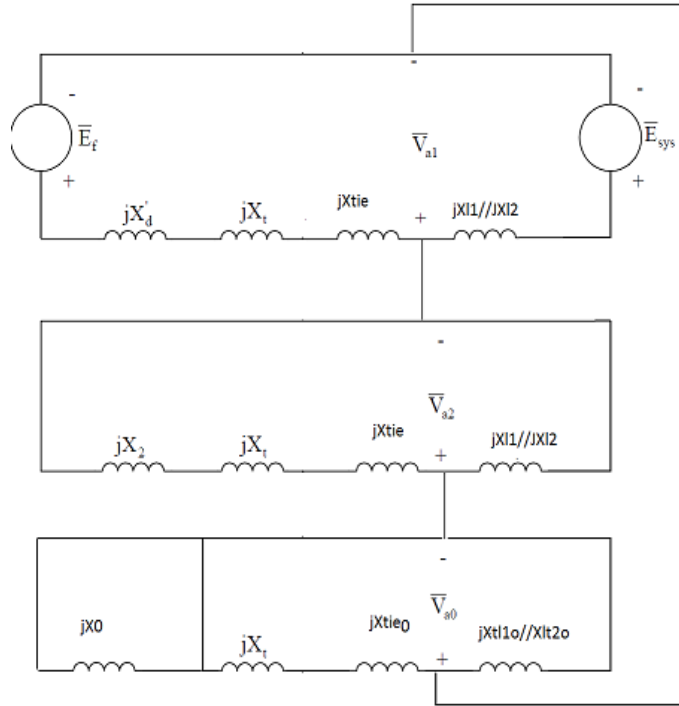


Fig 3.6 sequence network representation of Fig 3.5 for SL fault

Table 3.4 per unit representation of all the transmission line data

description		Positive sequence X(pu)	Negative sequence X(pu)	Zero sequence X(pu)
Transmission line	2km	0.0019467	0.0019467	0.0061478
	3km	0.0029201	0.0029201	0.0092218
	5km	0.0048668	0.0048668	0.0153673
	49km	0.0476951	0.0476951	0.1506221
Transformer		0.12	0.12	0.12
Generator		0.336	0.3492821	0.1777229

The calculations are done below

converting all values on the base S=40MVA

$$1.85 \frac{40\text{MVA}}{38.9375\text{MVA}} = 1.85 * 1.0273$$

$$= 1.9\text{pu} = x_d$$

$$X_l = 3\text{km}$$

$$Z_b = Z_{bl} = \frac{132\text{kv}^2}{40\text{MVA}} = 435.6$$

$$X_l = 5\text{km}$$

$$X_l = \frac{2.12}{435.6} = 0.00487$$

$$X_{l\text{ sys}} = 0.00487 - 0.0029\text{pu}$$

Initial system condition

$$S = 0.9734\text{pu}$$

$$x_t = 0.12$$

$$\text{pf} = -0.8$$

$$x_l = 0.0029201$$

$$V_t = 1 < 0$$

$$x_{tie} = 0.0029201$$

$$x_d = 1.9$$

$$x_{t1} \backslash \backslash x_{t2}$$

The generator current is calculated as follows

$$= 0.01870372$$

$$I_{gen} = \left(\frac{0.9734}{1} \right) \cos - \text{pf} = 0.9734 < -36.87$$

Infinite bus voltage = E_{sys}

$$\begin{aligned} E_{sys} &= V_t - j(x_t + x_l + x_{t1} \backslash \backslash x_{t2}) I_{ge} \\ &= 0.811054166 < -27.248 \end{aligned}$$

Generator voltage behind a direct axis transient reactance

$$\begin{aligned} E_f &= (V_t + jx_d') I_{gen} \\ x_d' &= 1 < 0 + j0.336 * 0.9734 < -36.87 \\ &= 1.224518522 < 12.337 \end{aligned}$$

Initial power angle

$$\delta_o = 12.337 + 36.87 = 39.485^\circ$$

The maximum power

$$\begin{aligned} P_{max0} &= (E_f * E_{sys}) / X_{total} = 2.079357869\text{pu} \\ P_{mech0} &= P_{max} * \sin \delta_0 = 2.079357869 * \sin 39.485 \\ &= 1.325013096\text{pu} \end{aligned}$$

The reactance of the total system before fault = $x_d' + X_t + X_{tie} + X_{l1} // X_{l2}$

$$= 0.47762472\text{pu}$$

Since it is a SLG fault, the electrical power output of the generator will not be zero when the fault is on. To calculate the maximum power during the fault on, Figures above can be helpful to obtain the reactance needed. The equivalent reactance for the negative and zero sequence networks can be calculated as follows, respectively,

From figer 3.6 the equivalent system reactance is as follows

$$X_{eq2} = (X_2 + X_t + X_{tie}) // (X_{l1} // X_{l2}) = 1.862981144 * 10^{-4}$$

$$X_{eq0} = (X_0 + X_t + X_{tie}) // (X_{l1} // X_{l2}) = 1.859032314 * 10^{-3}$$

$$X_{during} = \frac{((X_d' + X_t + X_{tie})(X_{eq2} + X_{eq0}) + (X_{eq2} + X_{eq0})(X_{l1} // X_{l2}) + (X_d' + X_t + X_{tie})(X_{l1} // X_{l2}))}{(X_{eq2} + X_{eq0})}$$

$$= 0.691403793 \text{ pu}$$

To obtain the critical clearing angle for this case the equal area criteria graph is plotted By Matlab software

The following function gives the equal area plot the full code is shown on the appendix

$$P_m = 1.325013096; E = 1.224518522; V = 0.811054166;$$

$$X_1 = 0.47762472; X_2 = 0.691403793; X_3 = 0.456;$$

$$\text{eacfault}(P_m, E, V, X_1, X_2, X_3)$$

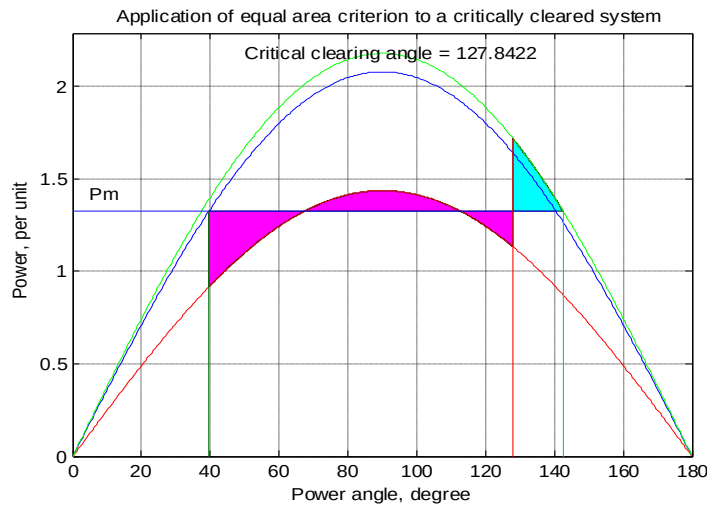


Fig.3.7 EAC curve for SL G fault

From the above graph the critical clearing angle is =127.8422 degrees

The critical clearing time can be obtained below

$$t_{cc} = \sqrt{\frac{2 \cdot H (\delta_{cc} - \delta_0)}{\pi \cdot f \cdot P_e}} = 0.244841904 \text{ sec} = 12.242 \text{ cycles}$$

3.3.2 Case 2 Three phase fault at the tie line ,switch yard, transmission line 2 ,transmission line1

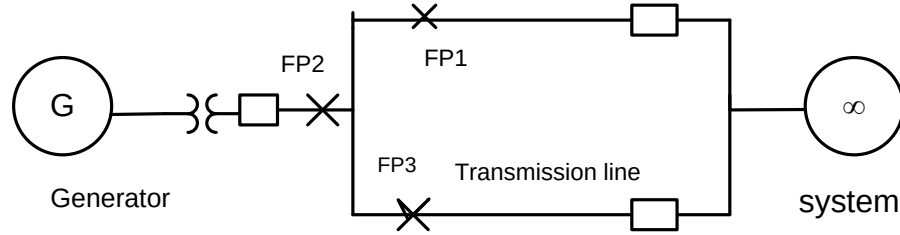


fig 3.8 Three phase fault point representation

If the fault occurs on fault point 1,2, 3 as shown on figer 3.8 it is not possible to isolate the line without interrupting the power export or import as such the power transferred during fault will be zero and the system will be separated without causing the tripping of the generator or the system hence the analysis shown below is done

similar to case 1

$$I_{gen} = \frac{S}{V_t} < -\cos^{-1}(PF)$$

$$I_{gen} = (0.9734/1) \cos-P.F = 0.9734 < -36.87$$

$$E_{sys} = V_t - j(x_t + x_l + X_{tl1}///tl2) I_{gen} = 0.811054166 < -27.248$$

$$E_f = V_t + j(x_d') \cdot I_{gen}$$

$$= 1 < 0 + j(0.336) \cdot 0.9734 < -36.87$$

$$= 1.224518522 < 12.337$$

$$\delta_0 = 12.337 + 36.87 = 39.485^\circ$$

The maximum power transfered

$$P_{max0} = (E_f \cdot E_{sys}) / X_{total} = 2.079357869 \text{ pu}$$

$$P_{mech0} = P_{max} \cdot \sin \delta_0 = 2.079357869 \cdot \sin 39.485$$

$$=1.325013096\text{pu}$$

total reactance before the fault=0.44762472

total reactance during fault=inf

total reactance during fault=0.336+0.12=0.456

using matlab software for evaluating the critical clearing angle and the plot of equal area criteria the following function is used the total code is shown on the appendix

from the plot the critical clearing angle=72.5779

$$H=1 \cdot J \cdot \omega_s / 2S_n = 0.5 \cdot (12825.07 \cdot 157^2) / 38937.5 \cdot 10^3$$

$$=4.05$$

the machine inertia constant =4.05

$$t_{cc} = \sqrt{\frac{2H(\delta_c - \delta_0)}{\pi f P_{mec}}} \quad \text{eq (3.7)}$$

Initial power angle = 39.585

Maximum angle swing = 142.528

Critical clearing angle = 72.578

Critical clearing time = 0.137 sec.

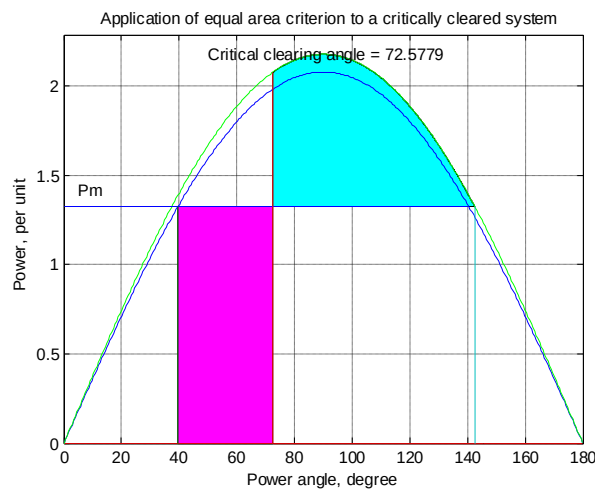


fig 3.9 EAC curve for three phase fault

3.3.3 CASE 3 Three phase fault at the tie line ,switch yard, transmission line 2 ,transmission line with factory load modeled by constant impedance

when a the factory load is modeled by a constant impedance

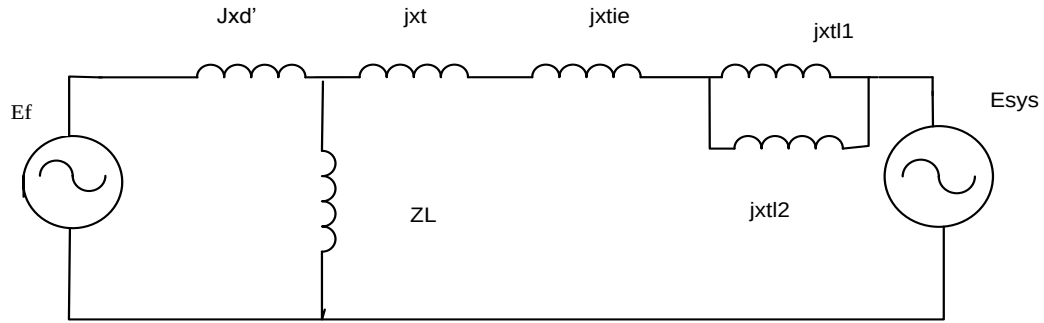


Fig 3.10 single line diagram with factory load modeled by constant impedance

$$P \text{ load} = 10\text{MW}$$

$$p. f. = 0.8$$

$$Q = 7.5\text{Mvar}$$

$$Z = \frac{V^2}{S} = \frac{(11)^2}{12.5} = 9.68 < 36.8^\circ$$

with the same base used on case one analysis

$$Z = 2.56 + j1.916\text{pu}$$

by making the tevnine equivalent of the system shown on fig 3.10

$$Z_s = \text{load}$$

$$y_{10} = \frac{Z_l}{jxd'z_l + jxd'z_l + z_lz_s}$$

$$= \frac{j0.14162382}{j0.337 * 2.56 + j1.916 + j0.337 * j0.141623 + j0.14162382 * 2.56 + j1.916}$$

$$y_{20} = \frac{jxd'}{jxd' * z_s + jxd'z_l + z_l * z_s} = 0.1891 + j0.1339$$

$$y_{12} = \frac{z_s}{jxd'z_s + jxdz_l + z_lz_s} = -0.0516 - j1.9648$$

doing the analysis as previous cases

The generator current

$$I_{gen} = \frac{S}{V} = 0.9734 \angle -36.87^\circ$$

Infinite bus voltage

$$E_{sys} = (-I_{gen} + (y_{10} + y_{12})E_{gen})/y_{12}$$

$$E_{sys} = \frac{(y_{10} + y_{12})E_{gen} - I_{gen}}{y_{12}} = 0.7793 \angle -28.2^\circ$$

Generator voltage

$$E_f = V_t + jx_d' I_{gen} = 1.2202 + 0.2936i$$

$$= 1.255025 \angle 13.529^\circ$$

since the factory load is predominantly inductive

$$P_{max} = E_{sys} * E_f / X_{12} = 1.292106$$

$$P_o = P_{max} * \sin \delta = 1.2786$$

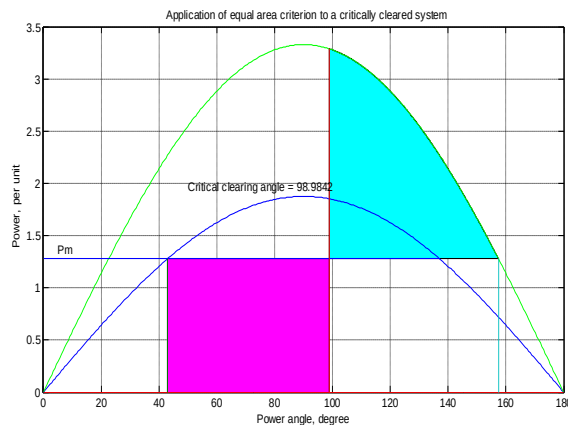


fig 3.11 EAC curve for case three

$P_o = 1.278678637$; $E = 1.225025$; $V = 0.7793$; $X = 0.50911$;

`eacpower(Po,E,V,X)`

3.4 Under frequency load shedding calculation procedure

One way of determining the frequency response of a system for determining the under frequency load shedding setting of relays is to use frequency response models. One method of estimating frequency behavior for this purpose is to model the frequency decline following the

disturbance using a model that reflects the load and generator behavior. This model results in a first-order differential equation that has the solution.[10]

$$\Delta w(t) = \frac{P_{step}}{D} \left(1 - e^{\left(\frac{D}{2H}\right)t} \right) \quad eq(3.8)$$

This model, which is attractive for its simplicity, describes the frequency trajectory as it falls from its initial value in an exponential fashion. The rate of decline is faster than that predicted by SFR model since it does not model the governor behavior. The slope of the frequency function using this model is given by

$$\frac{d\Delta w}{dt} = \frac{P_{step}}{2H} e^{(-D/2H)t} \quad eq(3.9)$$

This model is often used for determining the time at which load shedding relays should be employed. The initial slope computed by SFR is exactly the same as that computed by eq(3.9). Note that only the inertia and damping are required to find the frequency for any disturbance of any size, since the governor behavior is ignored.[10]

3.4.1 System frequency response analysis

The dynamic performance of the system with respect to change in total generation and load can be represented by swing equation [17]. The relationship that define variation of frequency with total generation and load mismatch can be obtain from swing equation,

$$\begin{aligned} 2H * \frac{dw}{dt} &= P_m - P_e = P_a \\ \frac{GH}{\pi f_0} * \frac{d^2\delta}{dt^2} &= p_m - p_e = p_a \\ w &= w_0 + \frac{d\delta}{dt} = 2\pi f \\ \frac{dw}{dt} &= \frac{d^2\delta}{dt^2} = \frac{2\pi df}{dt} \\ \frac{df}{dt} &= \frac{p_a f_0}{2GH} \end{aligned} \quad eq (3.11)$$

where:

G: nominal MVA of generator

H: inertia constant

δ : generator rotor angle

f_0 : nominal frequency

P_a : net accelerated or decelerated power (mismatch between generation and load)

The cogeneration facility at WSSF has the capacity to generate 31.15MW since the factory load is 10 MW even if the plant is generating its half capacity the load shedding is not necessary but by observing the plants performance of the past years there are events that the plant is generating a quarter of its capacity and the total factory load is supplied by both the grid and the cogon ,in the event of tie line tripping the governor of the system should respond fast but due the operational character and the boiler operation this may not be effective since the necessary steam may not be supplied and the factory may go to total shutdown to avoid this scenario after the tie line tripping the plant will go on tie line undercurrent supervised under frequency load shedding .

If we assume the tie line is opened when the plant was importing 5 MW which is the worst case scenario the frequency decay is determined be eq (3.11) as shown below

$$\begin{aligned}\frac{df}{dt} &= \frac{P_a}{G} * \frac{1}{2H} * f_0 \\ &= \frac{\frac{5MW}{31.25}}{2*4.05} * f_0 = 0.019816 \frac{pu}{s} \\ &= 0.019816 * 50 = 0.99Hz/sec\end{aligned}$$

It is possible that for industrial cogeneration plant to have a system overload up to 100% .The figure below shows the frequency decay for different amounts of system overload with the constant system inertia equal to 4.05.

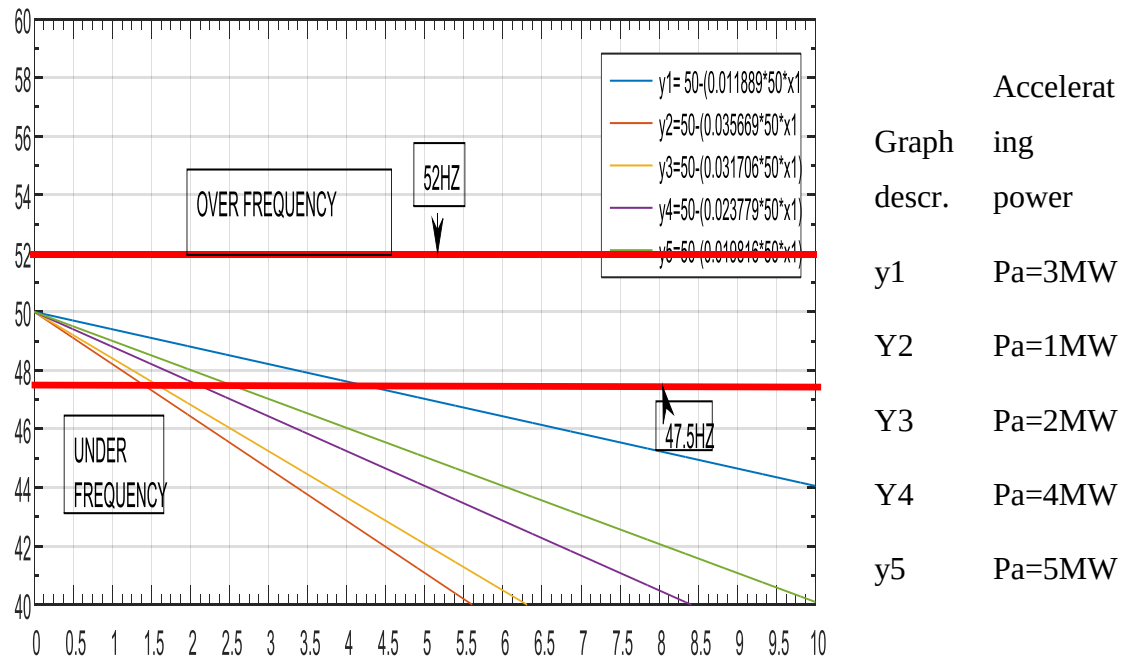


Fig 3.12 SFR with out the effect of governer and damping

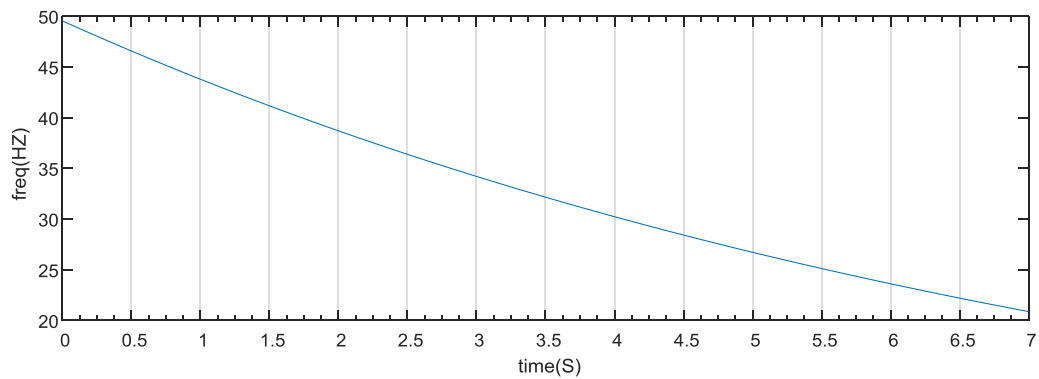


Fig 3.13 (a) frequency response of WSSF power system when decaying exponential frequency response model is used

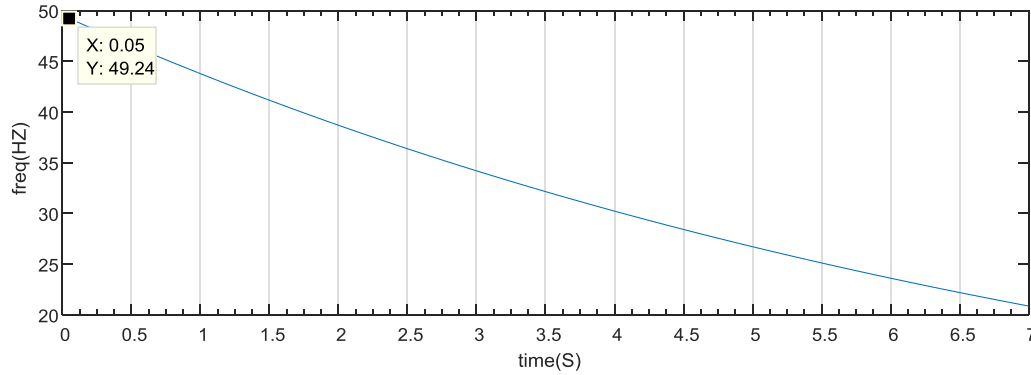


Fig 3.13(b) frequency response of WSSF power system when decaying exponential frequency response model is used time stamp of 0.05sec and 49.24 HZ

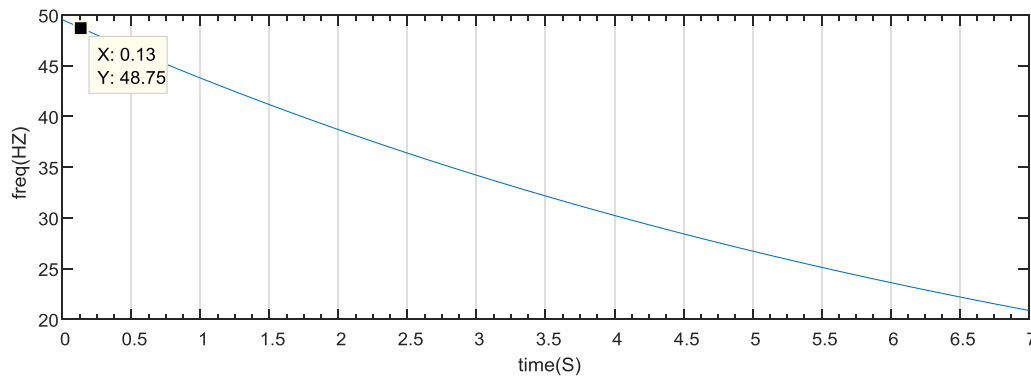


Fig 3.13(c) frequency response of WSSF power system when decaying exponential frequency response model is used time stamp of 0.13sec and 48.75 HZ

Fig 3.13 a,b,c shows frequency response when decaying exponential frequency response model is used. Since it is possible to determine the system frequency decay of the system, it is also possible to postulate the recovery characteristics from the same equation. For example, if an increment of load equal to the overload is shed, the torque T_a will be zero hence the accelerating power will also be zero and therefore the rate of change of frequency will be zero. The frequency would remain at the value it had reached at the time the load had been shed. This load shedding program is developed to protect the WSSF power system in the event of maximum overload as stated above. The amount of load shed should be sufficient to

restore system frequency to normal or close to normal (above 50 Hz). To accomplish this, it would mean the load that is shed should nearly equal the amount of overload, .It is not essential that the frequency be restored exactly to 50 Hz. If the frequency is restored above 49 Hz, the remaining system generation may pick-up the remaining overload through speed-governor action and restore the frequency to normal. If the generation does not have pick-up capability, operation above 49 Hz will not be detrimental and the system operator will have ample time to drop additional load or add generation. Because of the possibility of damage to steam-turbines, it is not recommended that less load be shed and thereby permit system frequency to settle-out at some level below 49hz.

Load shedding programs are usually designed to shed load in steps, to minimize the possibility of shedding too much load during less severe overload conditions. Moreover, the load shed at each step is usually distributed at a sufficiently large number of points around the system or interconnected systems to minimize spurious power swings, which may cause tripping of major transmission lines and/or tie-lines in this particular system total black out .

3.4.2 Initiation of Load Shedding - Frequency Level

The frequency level at which load shedding is initiated depends on several factors. For one, the level should be below any frequency drop from which the system could recover or below any frequency at which the system could continue to operate. On isolated systems, systems without interconnections, it may be reasonable to operate at some reduced frequency

3.4.3 Permissible Frequency Reduction

The load shedding programs must be coordinated with equipment operating limitations during low frequency operation. These limitations are usually associated with operation of power plant auxiliaries.

3.4.4 load shedding steps for WSSF cogeneration plant

Taking the above points into consideration and from the calculation done on page 36 a system frequency response curve is selected for this analysis from the system setting and fig3.11..the

maximum allowable frequency drop is 47 Hz in which the system could operate hence a load shedding is initiated

- 1st step 2 MW20% the load
pick up setting 49hz
relay delay time 0.15
breaker delay time 0.1
- 2nd step 3MW.....30% of the load
pick up setting 48.8hz
relay delay time 0.15

The second step must be set so that it will not operate for an overload which only requires shedding by the first step. In other words, for a 30% percent overload, the pick-up setting of the second step should be such that the first step of load is shed before the frequency reaches the Step 2 setting. Curve y5 in Fig.3.11 shows a 50 percent overload condition. The first step relay R1 picks up at 1.015 seconds and load is shed at 49 Hz and 1.55 seconds. The Step 2 relay can be set at 48.8 or slightly lower. In this case, a setting of 48.8 Hz is chosen to provide additional margin. The time setting of this step is also 0.25 second.

Simulation of single line diagram of the WSSF power system is done on is done on ETAP on the contingency that the tie line is tripped while the cogeneration plant is generating 5MW and the rest of the factory load is supplied from the grid .The resulting out puts are shown on result section.

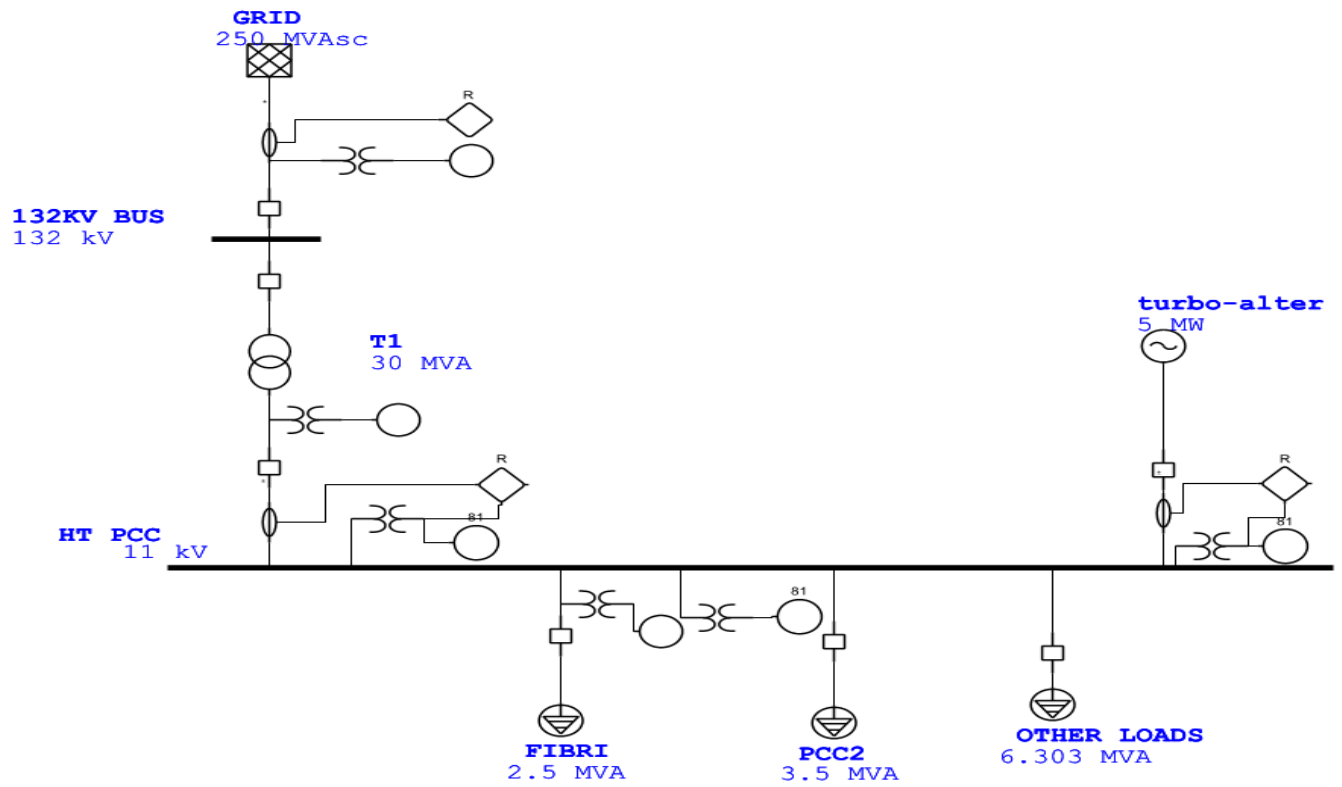


Fig 3.14 WSSF power system modeled on ETAP for load shedding and islanding analysis

As it is seen from the figure after the simulated outage occurs the load shedding is initiated at 49Hz with a time delay of 1.05sec and trips the F11 breaker dropping 2MW and another 3 MW by opening F20 after the delay of 1.211 this reducing the total load of the factory to 5MW which is equal to the generation and giving the plant operators time to increase their generation either by starting the diesel generators or by increasing their boiler feeding and producing more steam while the factory is partially running and significant process are not interrupted.

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

In chapter three the WSSF power system was modeled as OMIB and the system was analyzed for different types of faults at various points on the transmission line and based on that critical clearing angle and critical clearing time for the circuit breakers were determined all the simulations were done on MATLAB and ETAP software.

Based on the modeling and simulations done on chapter 3 on matlab software for determining the critical clearing angles of for a fault at different part of the transmission line a swing curve is used to determine the system stability and critical clearing time of the system.

4.1 Result swing curves of case 1,2,3

case 1

single phase to ground fault at transmission line 2

From Fig 3.7 the critical clearing angle is =127.8422 degrees

the critical clearing time can be obtained below

$$t_{cc} = \sqrt{\frac{2 \cdot H(\delta_{cc} - \delta_0)}{\pi \cdot f \cdot P_e}} = 0.244841904 \text{ sec} = 12.242 \text{ cycles}$$

hence for obtaining the exact critical clearing time and evaluating its validity the swing curve is plotted as follows by using the a matlab code which uses modified Euler method.

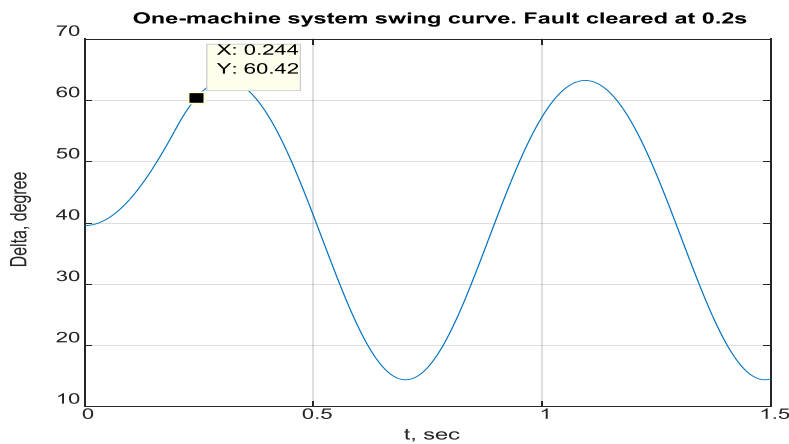


fig 4.1 one machine system swing curve for fault cleared at 0.2 sec

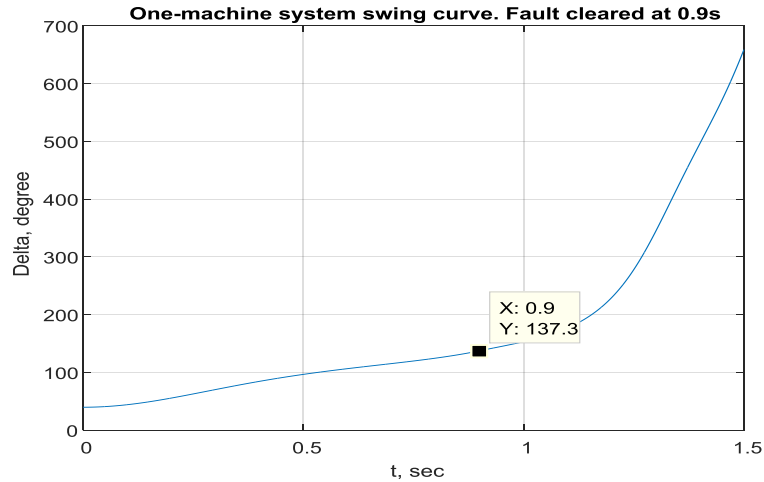


fig 4.2 one machine system swing curve for fault cleared at 0.9 sec

Fig 4.2 shows the a one machine system with single line to ground fault cleared at 0.9 sec the swing curve shows a fault cleared at this time leads to instability

As it seen in the figure for faults that are far from the cogeneration plant the the breaker should trip with in 0.244 sec for the system to remain stable

Case 2 Three phase fault at one of the places switch yard transmission line one or two ,or the tie line in all the cases as shown in figer 3.8 ,

During fault there is no power transmission in the system and from Fig 3.9 EAC plot the critical clearing angle is $=72.5779$ the resulting swing curve plot are shown bellow

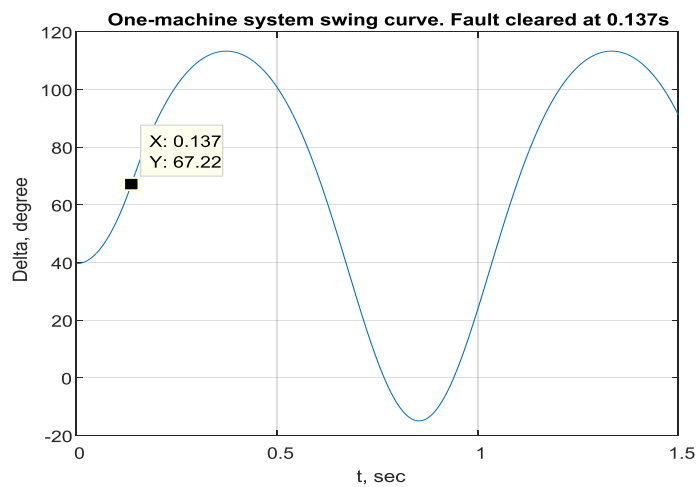


Fig 4.3 one machine infinite bus system fault cleared at 0.137sec

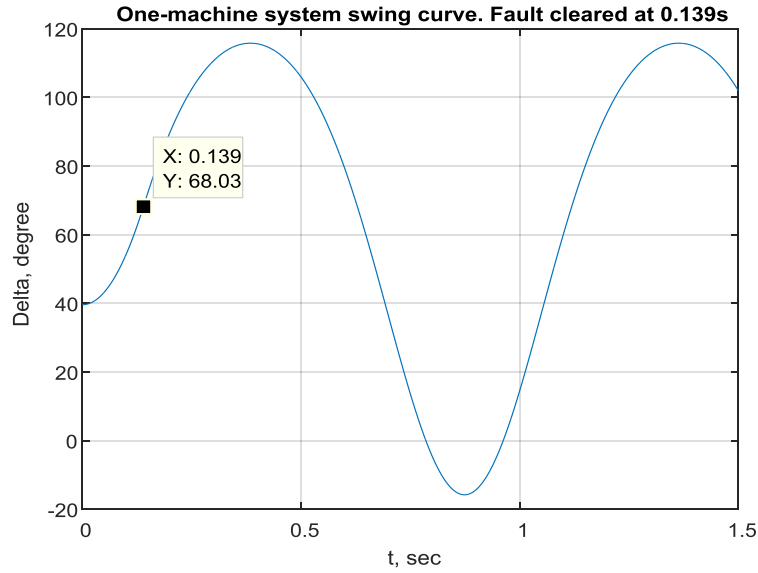


fig 4.4 one machine system swing curve for fault cleared at 0.139 sec

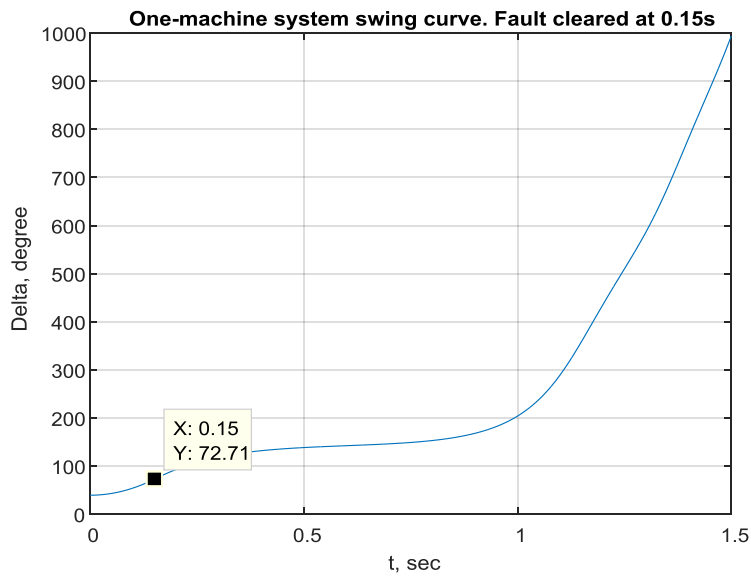


fig 4.5 one machine system swing curve for fault cleared at 0.15 sec

As it is seen on fig 4.3 and fig 4.4 if a three phase fault at any the places described in this case should be cleared in 0.137-0.139 sec for the system to remain transiently stable faults cleared at $t_c \geq 0.15$ sec leads to instability.

Case 3 The system could be stable if fault is cleared with in 0.181 sec

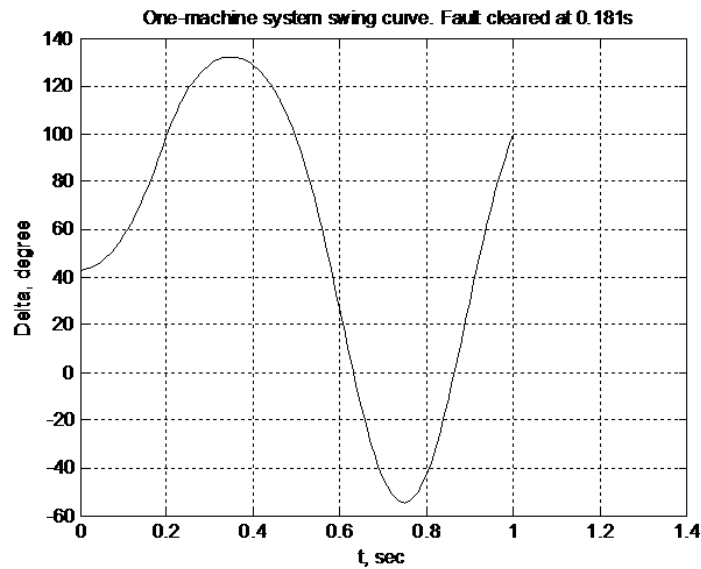


fig 4.6 one machine system swing curve for fault cleared at 0.181 sec

For case three from fig 3.10 and from fig 4.6 above ,the fault should be cleared at $t_{cc}=0.181\text{sec}$ for the system to remain stable

4.2 Analysis of the de-coupling settings

The aim of this analysis is to provide secure islanding of WSSF plant in case stability endangering faults. The negotiated case is the outage of the neighborhood 132 kV bus feeding the WSSF loop due to various sorts faults. The computer simulations were done ETAP.

4.2.1 Relay setting for tie line tripping

To make sure the power quality, power supply reliability, and utility safety operation of cogeneration plant after connecting to the national grid system, the cogeneration plant have installed different types of protection relays. When fault occurs on the tie line as well as transmission line connecting the two systems it is imperative that the two system get separated before a disturbance is resulted on cogeneration generator units or significant loads tripping inside the plant, this is achieved by coordinating the protection system inside the plant and having them take action at exact time. To realize the above statement WSSF has installed

distance relay and differential relays for the line and transformer protection in addition the numerous numerical relays at each feeder.

The most savior faults in power system are usually the three phase faults ,a simulation of a WSSF power system shown on fig 3.14 single line diagram was done on ETAP with the calculation and the results of the modeling that is done on mat lab and the following outputs or results are found.

For stable of operation of the power system the fault that occurs on 132kv tie line must be cleared by the directional over current relay within 0.137 second and the circuit closer to the fault must respond first after the occurrence of fault else the system will go to total black out. Faults that occur beyond the tie line and the adjacent transmission line the distance relay will be active. From the company profile and its past records of power generation data the cogeneration plant most of the time generates power equal to its home load ,and same times exports power and sometimes imports power.

MODE1

when the WSSF power system is working synchronized with the grid supply while power generated by the WSSF generator is equal to its home load and fault cleared on the above described time. The figures show that after the clearance of the faulted line by decoupling the two system the WSSF power system remain stable and the generator continues to supply the factory load.

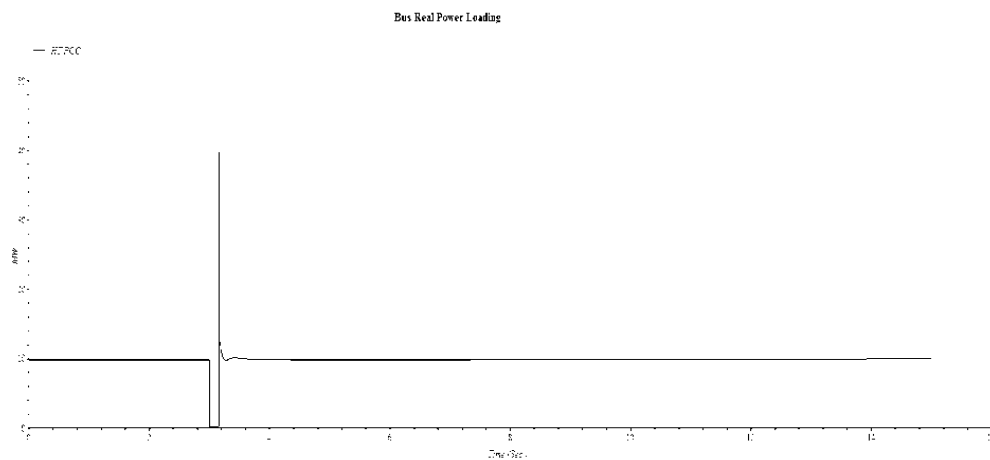


fig 4.7 11 kV (HT PCC) real power loading with respect to time

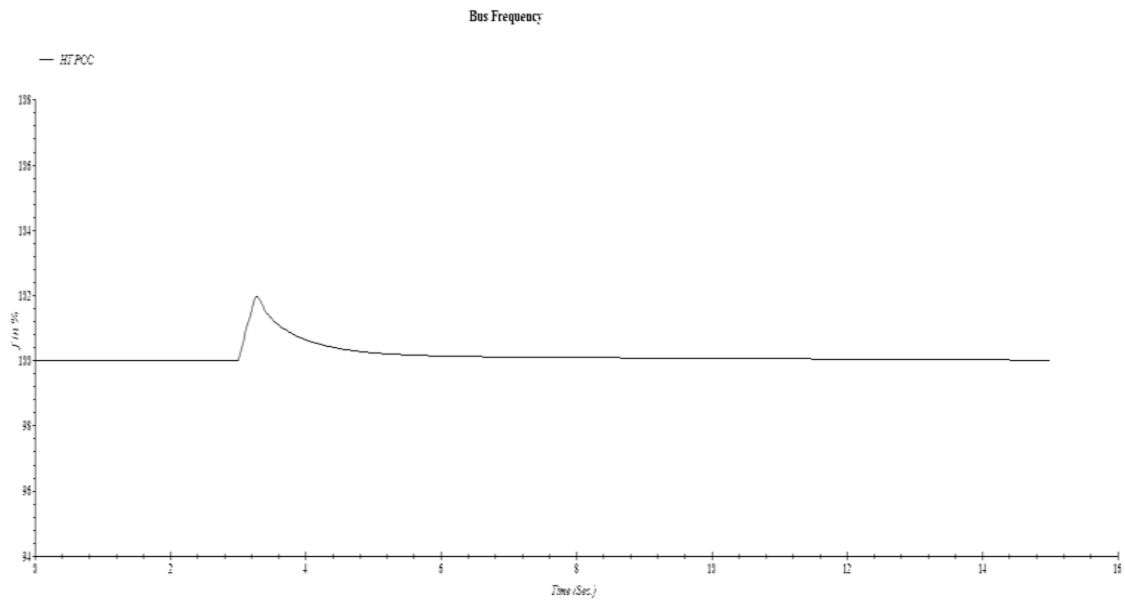


fig 4.8 11 kV (HT PCC) bus frequency with respect to time

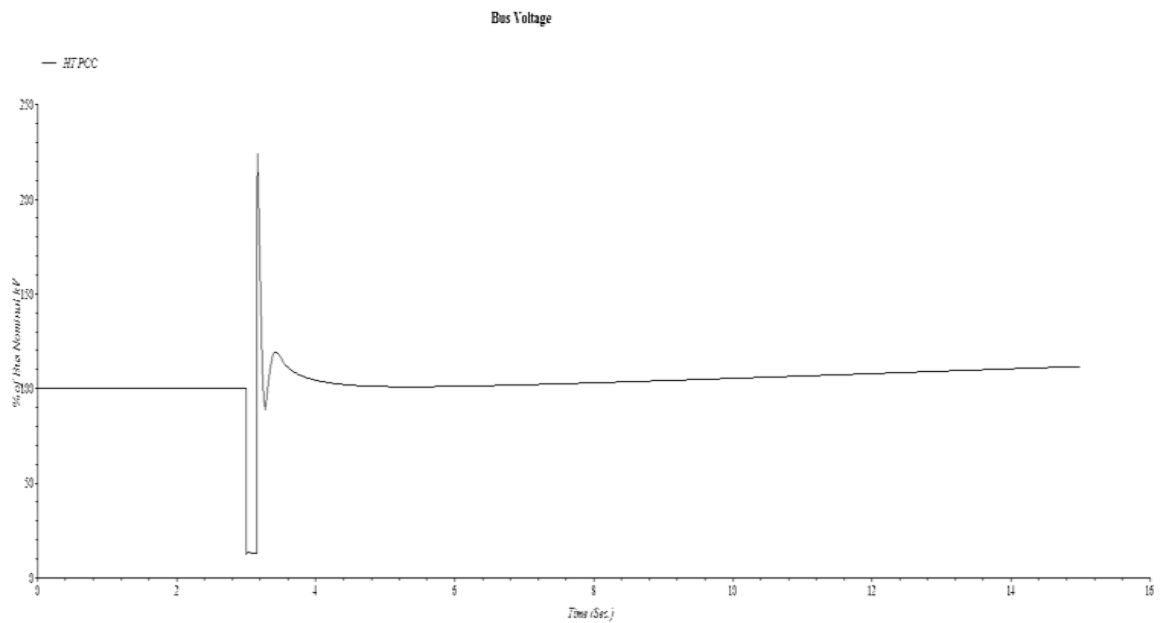


fig 4.9 11 kV (HT PCC) bus voltage with respect to time

MODE 2

The simulation on this mode is carried out on the bases that the WSSF generator is working synchronized with grid supply but power generated is less than the home load

In this case after decoupling of the system the frequency and voltage will drop drastically unless a proper mitigation is kept in place ,in other words a load shedding scheme is required for this particular research and from in plant observation it is found a 5MW generation is the list quantity they would generate and the rest of the power demand is fulfilled from the national grid, Taking this in to consideration a load shedding is developed for this particular case below.

Table 4.1 load shedding data

step	Load shaded(MW)	Frequency(Hz)	Time(sec)
First step	2MW	49	1.015
Second step	3MW	48.8	1.55

- ETAP simulation results for mode two without load shedding

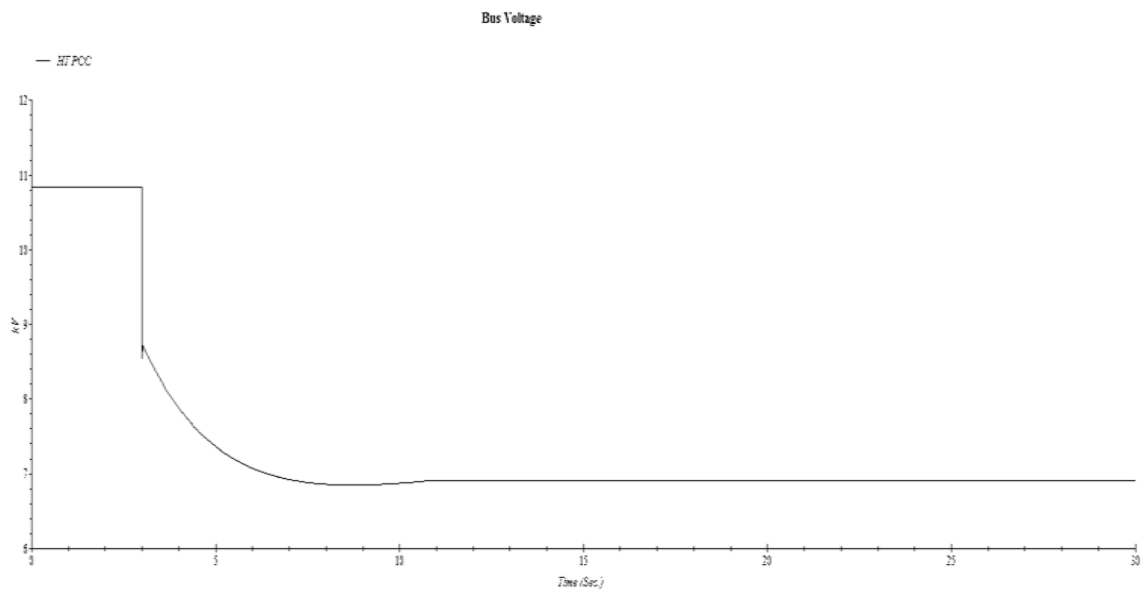


fig 4.10 11 kV (HT PCC) bus voltage with respect time for MODE 2

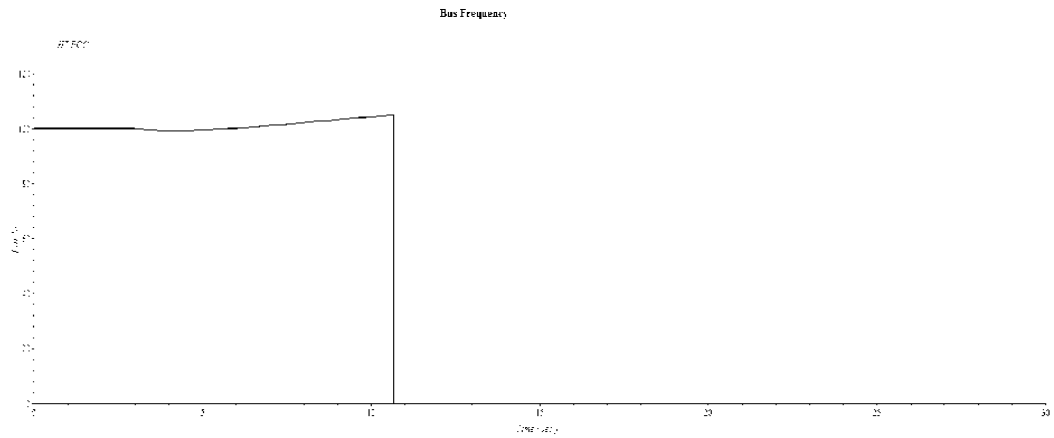


fig 4.11 11 kV (HT PCC) bus frequency with respect to time for MODE 2

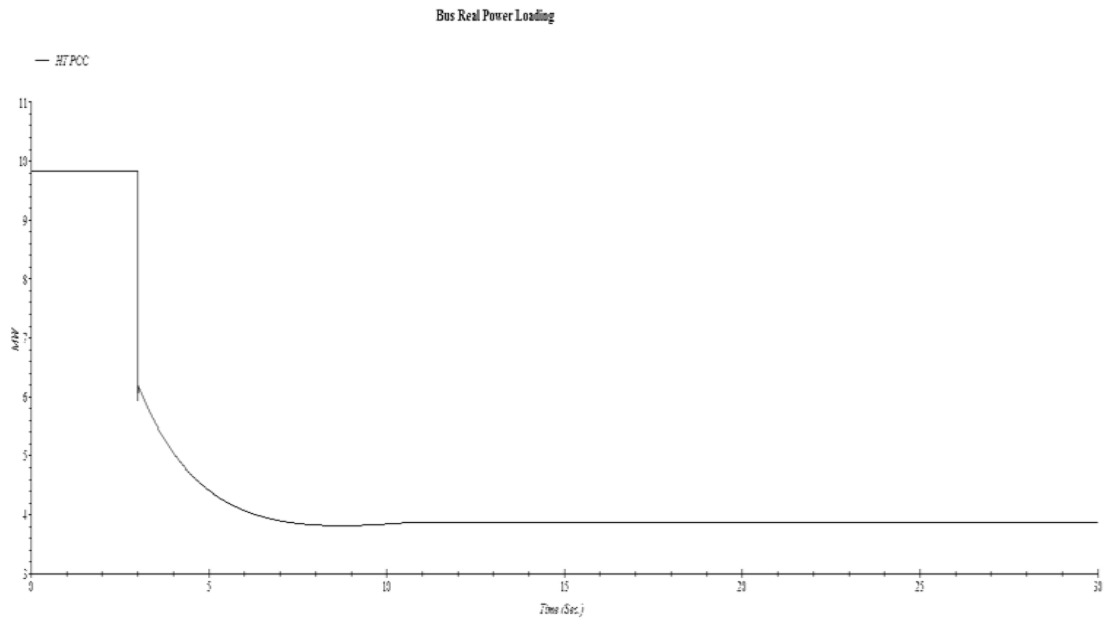


fig 4.12 11 kV (HT PCC) real power loading with respect to time for MODE 2

From the simulation it is observed that the voltage and frequency on the high tension bus (HT PCC) drops to 65% of the rated with in 3 sec of the outage of the tie line and after the system collapses.

The resulted output wave forms load(MW),voltage and frequency at HT PCC bus of WSSF power system after the implementation of the proposed load shedding schemes.

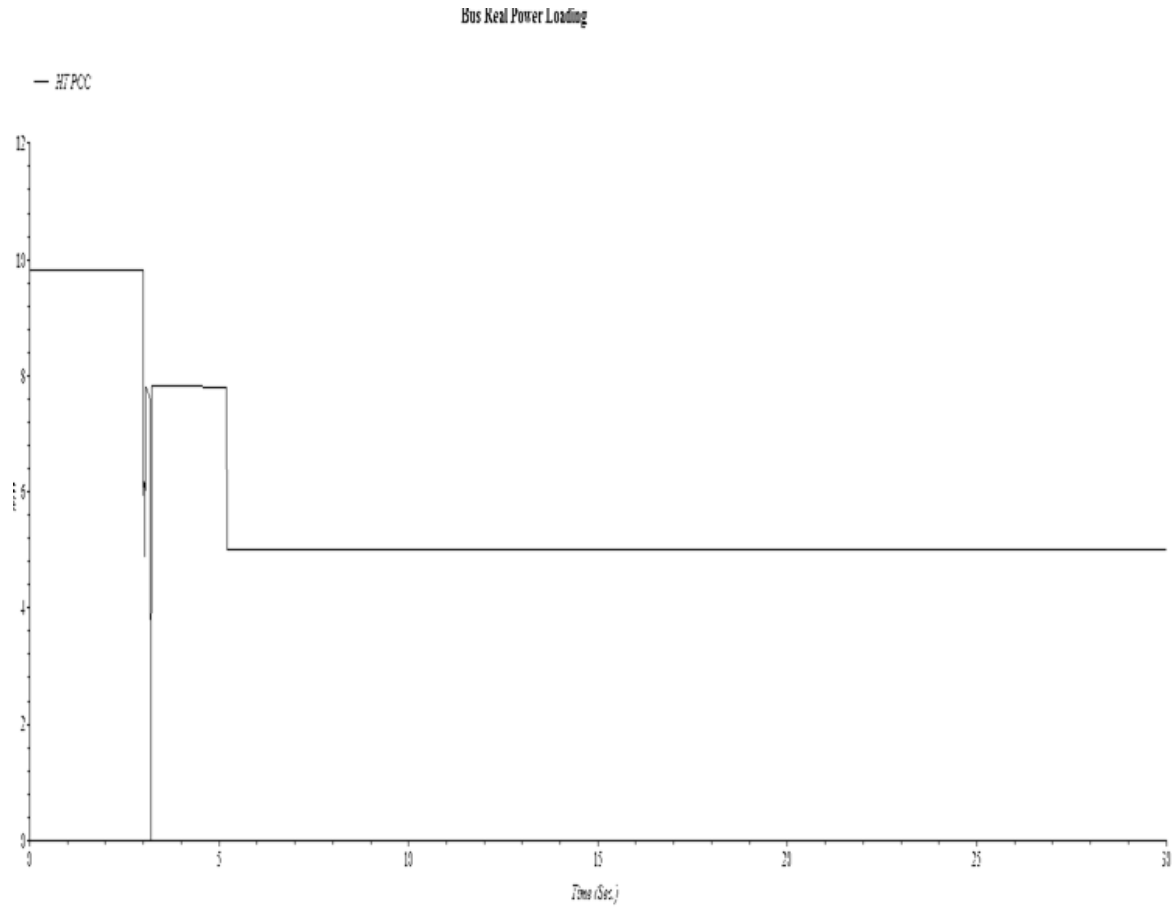


fig 4.13 11 kV (HT PCC) real power loading with respect to time for MODE 2 after load shedding

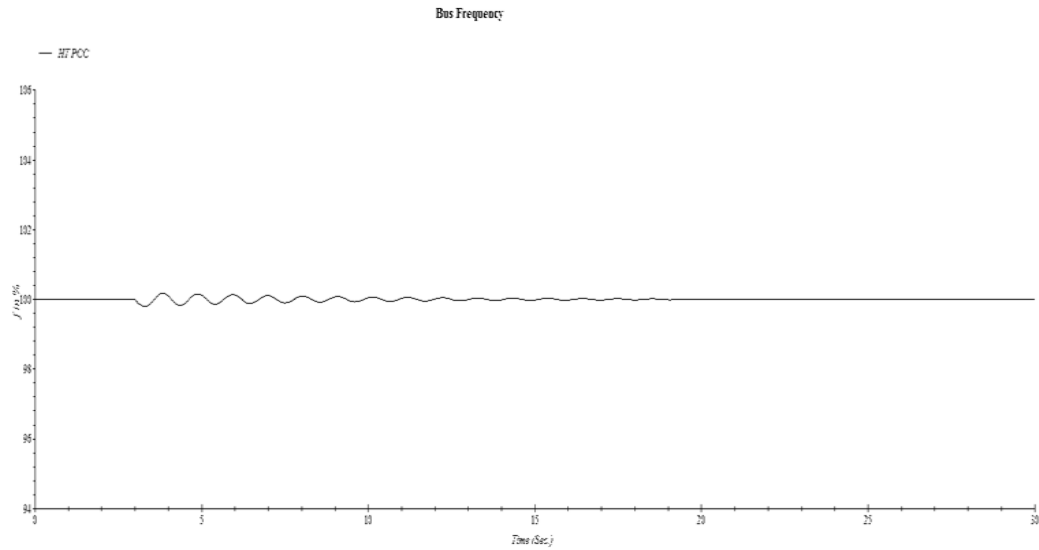


fig 4.14 11 kV (HT PCC) frequency with respect to time for MODE 2 after load shedding

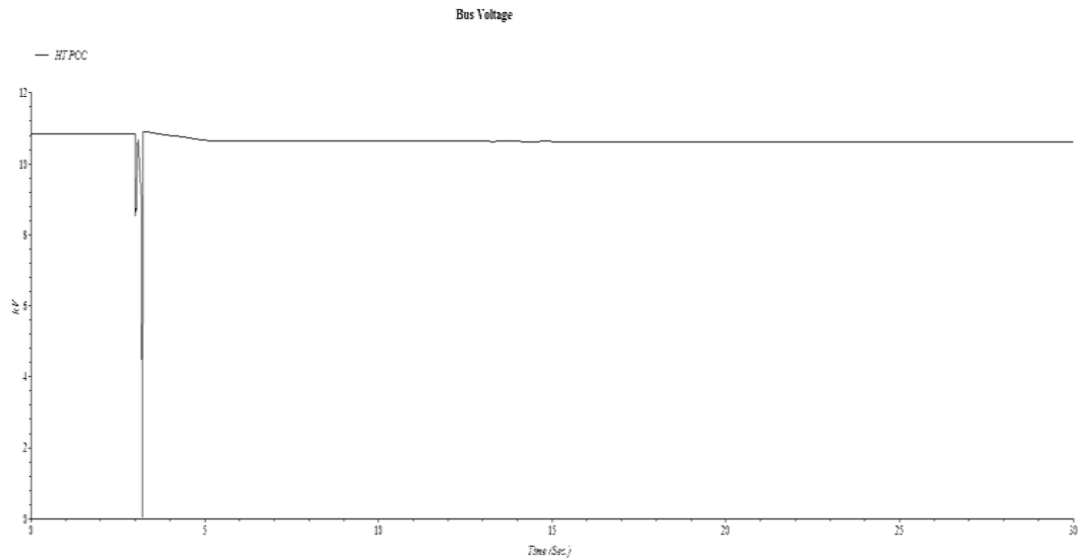


fig 4.15 11 kV (HT PCC) bus voltage with respect to time for MODE 2 after load shedding

From the above figures of 11kv bus voltage ,frequency, real power loading the successful application of load shedding prevents the system collapse that was observed on the simulation without load shedding.

4.2.2 Discussion on relationship between reliability and stability

Since reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period. while Stability of a power system, as discussed in chapter 2 refers to the continuance of intact operation following a disturbance. From the historical data that is gathered from WSSF the reliability index such as failure rate and mean time between failures for the whole system were found to be

failure rate $\lambda = 1.255 \times 10^{-3}$ failure/hr and the MTBF = 796.36 hr

For a power system to be reliable, the power system must be secure most of the time. To be secure, the system must be stable but must also be secure against stability endangering contingencies. The simulation done for the decoupling scheme and load shedding on ETAP software with the results obtained on MATLAB software shows that for the contingency taken in to consideration the system remain stable hence ,Applying the changes on CCT values on the protection settings greatly improve the reliability of the system.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This thesis has investigated the protective relay settings for the tie lines tripping by the transient stability analysis to enhance the dynamic responses of the cogeneration system when it is operated in autonomous condition. The transient stability analysis has been performed to derive the critical clearing time for the settings of instantaneous operation of directional over current and under voltage relay. By this way, the tie lines can be tripped in a very short time period for the nearby serious fault. Also, the under frequency relay is designed to trip the tie lines according to the characteristic of the utility and cogeneration plant in addition the study has shown the need of performing transient stability studies on industrial systems with co-generating units for improving both the reliability and post-contingency system response, either for isolated system operation or when connected to the utility grid.

For increasing the reliability of the cogeneration plant load shedding was applied to the cogeneration system under different tie line tripping opportunities and operation modes .Both the islanding and interconnected modes of operations have been modeled in MATLAB and ETAP via the operation of circuit breakers ,which allows transition from interconnected to isolated mode.

The mechanism of tie line tripping is very important between cogeneration plant and the EEP system. This being said in addition to the frequency relays activity, we can also utilize the under voltage relays to perform a proper load shedding. In this way, the improper tie line tripping can be avoided due to the internal fault of cogeneration system, and the both power systems of the EEP and cogeneration plant can keep normal independent operation after tie line tripping.

5.2 Recommendation

It is recommended that further study should be done to modify the thesis even though the simulations done show satisfactory results other studies need to be done for enhancement of the transient stability of the WSSF power system by other methods other than fast clearing of the faults and disturbances.

REFERENCES

- [1] Hung-Cheng, Chen Shang-Yi ,Chen Shun-Chung Shih "Transient Stability Analysis of an Industrial Cogeneration System "Department of Electrical Engineering, National Chin-Yi University of Technology,2010
- [2] Abdul Malek Miah , “A new method of transient stability assessment by using a simple energy margin function, ”Second International Conference on Electrical and Computer Engineering Dhaka, Bangladesh, pp. 24–27, 26-28December 2002
- [3] Sonali Raj1, Preeti Jain2"Comparative Study of Different Methods of Transient Stability Assessment "International Journal of Novel Research in Electrical and Mechanical Engineering Vol. 3, Issue 1, pp: (14-18), Month: January-April 2016, pp16-18

- [4] Joao Pedro de carvalho Mateus ,IST "Electric Power Transient stability analysis techniques" <http://fenix.tecnico.ulisboa.pt.resmo>
- [5] E. Joh McConnell, "Industrial Cogeneration - Insights and Observations," Industry Applications, IEEE Transactions on , vol.IA-19, no.4, pp.614-618, July 1983
- [6] P. Kundur, N. J. Balu, and M. G. Lauby, Power System Stability and Control McGraw-Hill New York, 1994.
- [7] Jignesh S. Patel, Manish N. Sinha (13-14 May 2011), "Power System Transient Stability Analysis Using ETAP Software". IEEE National Conference on Recent Trends in Engineering & Technology, B.V.M. Engineering College, V.V.Nagar,Gujarat,India
- [8] C. Chen, C. Hsu, Y. Lee, J. Huang, H. Chen, and C. Huang, \Under Frequency Relay Setting for Tie Line and Load Shedding of an Industrial Power System with Multiple Cogeneration Units," in Pulp and Paper, 1999. Industry Technical Conference Record of 1999 Annual. IEEE, 1999, pp. 184{189.
- [9] R. A. J. Khan, M. Junaid, and M. M. Asgher, \Analyses and Monitoring of 132kV Grid Using ETAP Software," in Electrical and Electronics Engineering, 2009.ELECO 2009. International Conference on. IEEE, 2009, pp. I{113.
- [10] H.-C. Chen, S.-Y. Chen, S.-C. Shih et al., \Transient Stability Analysis of anIndustrial Cogeneration System," 2010.
- [11] Chandra S. Sherma /Transient stability analysis of single machine infinite bus system by numerical method /International Journal of Electrical and Electronics Research ISSN 2348-6988 (online) Vol. 2, Issue 3, pp: (158-166), Month: July - September 2014, Available at: www.researchpublish.com
- [12] Hadi Saadat,(1999), Book: "Power System Analysis" ,WCB McGraw-Hill International Editions.

APPENDIX

1. Matlab code for Plotting power angle curve(equal area criteria)

```
function eacfault(Pm, E, V, X1, X2, X3)
if exist('Pm')~=1
Pm = input('Generator output power in p.u. Pm = '); else
end
if exist('E')~=1
E = input('Generator e.m.f. in p.u. E = '); else
end
if exist('V')~=1
V = input('Infinite bus-bar voltage in p.u. V = '); else
end
if exist('X1')~=1
X1 = input('Reactance before Fault in p.u. X1 = '); else
end
if exist('X2')~=1
X2 = input('Reactance during Fault in p.u. X2 = '); else
end
if exist('X3')~=1
X3 = input('Reactance after Fault in p.u. X3 = '); else
end
Pe1max = E*V/X1; Pe2max=E*V/X2; Pe3max=E*V/X3;
delta = 0:.01:pi;
Pe1 = Pe1max*sin(delta); Pe2 = Pe2max*sin(delta); Pe3 = Pe3max*sin(delta);
d0 =asin(Pm/Pe1max); dmax = pi-asin(Pm/Pe3max);
cosdc = (Pm*(dmax-d0)+Pe3max*cos(dmax)-Pe2max*cos(d0))/(Pe3max-Pe2max);
if abs(cosdc) > 1
fprintf('No critical clearing angle could be found.\n')
```

```

fprintf('system can remain stable during this disturbance.\n\n')
return
else
end
dc=acos(cosdc);
if dc > dmax
fprintf('No critical clearing angle could be found.\n')
fprintf('System can remain stable during this disturbance.\n\n')
return
else
end
Pmx=[0 pi-d0]*180/pi; Pmy=[Pm Pm];
x0=[d0 d0]*180/pi; y0=[0 Pm]; xc=[dc dc]*180/pi; yc=[0 Pe3max*sin(dc)];
xm=[dmax dmax]*180/pi; ym=[0 Pe3max*sin(dmax)];
d0=d0*180/pi; dmax=dmax*180/pi; dc=dc*180/pi;
x=(d0:.1:dc);
y=Pe2max*sin(x*pi/180);
y1=Pe2max*sin(d0*pi/180);
y2=Pe2max*sin(dc*pi/180);
x=[d0 x dc];
y=[Pm y Pm];
xx=dc:.1:dmax;
h=Pe3max*sin(xx*pi/180);
xx=[dc xx dmax];
hh=[Pm h Pm];
delta=delta*180/pi;
if X2 == inf
fprintf('\nFor this case tc can be found from analytical formula. \n')
H=input('To find tc enter Inertia Constant H, (or 0 to skip) H = ');
if H ~= 0

```

```

d0r=d0*pi/180; dcr=dc*pi/180;
tc = sqrt(2*H*(dcr-d0r)/(pi*50*Pm));
else
end
else
end
%clc
fprintf('\nInitial power angle    = %7.3f \n', d0)
fprintf('Maximum angle swing    = %7.3f \n', dmax)
fprintf('Critical clearing angle = %7.3f \n\n', dc)
if X2==inf && H~=0
fprintf('Critical clearing time = %7.3f sec. \n\n', tc)
else
end
h = figure; figure(h);
fill(x,y,'m')
hold;
fill(xx,hh,'c')
plot(delta, Pe1,'-', delta, Pe2,'r-', delta, Pe3,'g-', Pmx, Pmy,'b-', x0,y0, xc,yc, xm,ym), grid
Title('Application of equal area criterion to a critically cleared system')
Title(Pe1,'before fault')
xlabel('Power angle, degree'), ylabel(' Power, per unit')
text(5, 1.07*Pm, 'Pm')
text(50, 1.05*Pe1max,['Critical clearing angle = ',num2str(dc)])
axis([0 180 0 1.1*Pe1max])
hold off;

```

Matlab code for plotting swing curve

```
function swingmeu(Pm, E, V, X1, X2, X3, H, f, tc, tf, Dt)
%global Pm f H E V X1 X2 X3
clear t
if exist('Pm')~=1
Pm = input('Generator output power in p.u. Pm = '); else, end
if exist('E')~=1
E = input('Generator e.m.f. in p.u. E = '); else, end
if exist('V')~=1
V = input('Infinite bus-bar voltage in p.u. V = '); else, end
if exist('X1')~=1
X1 = input('Reactance before Fault in p.u. X1 = '); else, end
if exist('X2')~=1
X2 = input('Reactance during Fault X2 = '); else, end
if exist('X3')~=1
X3 = input('Reactance after Fault X3 = '); else, end
if exist('H')~=1
H = input('Generator Inertia constant in sec. H = '); else, end
if exist('f')~=1
f = input('System frequency in Hz f = '); else, end
if exist('Dt')~=1
Dt = input('Time interval Dt = '); else, end
if exist('tc')~=1
tc = input('Clearing time of fault in sec tc = '); else, end
if exist('tf')~=1
tf = input('Final time for swing equation in sec tf = '); else, end
Pe1max = E*V/X1; Pe2max=E*V/X2; Pe3max=E*V/X3;
clear t x1 x2 delta
d0 =asin(Pm/Pe1max);
```

```

t(1) = 0;
x1(1)= d0;
x2(1)=0;
np=tf /Dt;
Pemax=Pe2max;
ck=pi*f/H;
for k = 1:np
    if t(k) >= tc
        Pemax=Pe3max;
    else, end
    t(k+1)=t(k)+Dt;

    Dx1b=x2(k);
    Dx2b=ck*(Pm-Pemax*sin(x1(k)));
    x1(k+1)=x1(k)+Dx1b*Dt;
    x2(k+1)=x2(k)+Dx2b*Dt;
    Dx1e=x2(k+1);
    Dx2e=ck*(Pm-Pemax*sin(x1(k+1)));
    Dx1=(Dx1b+Dx1e)/2;
    Dx2=(Dx2b+Dx2e)/2;
    x1(k+1)=x1(k)+Dx1*Dt;
    x2(k+1)=x2(k)+Dx2*Dt;
end
delta=180*x1/pi;

clc
fprintf('\nFault is cleared at %4.3f Sec. \n', tc)
head=['          '
      '   time   delta   Dw   '
      '   s     degrees rad/s'

```

```

    '
    '];
disp(head)
disp(['t', delta' x2'])
h=figure; figure(h)
plot(t, delta), grid
title(['One-machine system swing curve. Fault cleared at ', num2str(tc),'s'])
xlabel('t, sec'), ylabel('Delta, degree')
cctime(Pm, E, V, X1, X2, X3, H, f) % Obtains the critical clearing time

```

2 Data collected from WSSF factory log book

Table 1 causes of generator tripping on factory operation season of 2016/18

No	date	Reason	remark
1	10/02/16	Steam temp.low	Generator tripped
2	24/02/16	Nozzle jaming	Generator tripped
3	20/02/16	undervoltage	Generator tripped
4	10/03/16	Ro water sho.	Generator tripped.
5	11/03/16	Grid faller	Generator tripped
6	24/03/16	EEPtrip	Generator tripped
7	02/04/16	EEP TRIP	Generator tripped
8	06/01/16	EEP TRIP	Generator tripped
9	08/01/16	EEP trip	Generator tripped
10	10/02/16	EEP trip	Generator tripped
11	12/02/16	EEP trip	Generator tripped
12	13/08/18	EEP TRIP	Generator tripped

