STEADINESS TEST OF CONSECUTIVE POWER FLOW BY MEANS OF ELECTRIC LOAD REDUCTION

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A Thesis Submitted in Partial fulfillment of the requirements for the degree of
Master of Science in Electronics and Telecommunication Engineering

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APPROVAL

This Project titled "Steandiness Test of Consecutive Power Flow by Means of Electric Load Reduction", submitted by Amit Kumar Saha to the Department of Electronics and Telecommunication Engineering, Daffodil International University, has been accepted as satisfactory for the partial fulfillment of the requirements for the degree of M.Sc. in Electronics and Telecommunication Engineering and approved as to its style and contents. The presentation was held on 27-10-2019.

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Finally, I must acknowledge with due respect the constant support and patients of our parents.

ABSTRACT

The primary objective of this thesis is to investigate & study the transient steadiness of a Single Machine Infinite Bus (SMIB) system. The objective is due to the fact that the most desirable quality of an AC power Bus is steadiness. The definition of steadiness in this context is defined as the ability of the Bus to hold both the supply voltage & the voltage frequency to a constant value. In real life Power Bus, the value of frequency rarely changes, but value of voltage changes all the time. When power supply is less than the operating load, the frequency also reduces. The voltage changes may be due to the short comings of the power Bus & its relevant systems, the inability of the generators to provide enough power or due to the intensity of the load on the Bus. This thesis assumes the power Bus to be ideal i.e. no loss & also assumes that the generators are of sufficient capacity. Therefore only manipulative variable is the load. During the research, theoretical models for the relevant systems & sub systems were generated. Practical implementation of the said research is currently out of scope due to technical reasons e.g. the Bus bar works at 130 kv. Simulation models include generator model, load models (both static & dynamic) and reduced network model. The theoretical prediction is that steadiness can be improved via load curtailment. This prediction is tested during simulation. Before simulation a SMIB system is modelled with a load & infinite Bus. For the simulation fault points are designated at multiple points, one is explored at a time. Fault points include the secondary of power transformer, at the infinite Bus node & at the transmission node. The effect of fault is noted at the generator rotor angle & at the output power. Based on the result, multiple modes of curtailment are proposed that can help steadiness.

At faulty condition at Nde N4, the Critical Clearing Time = 0.2371 (sec) and Critical Clearing Angle = 65.1881 (deg). At Node N2, the Critical Clearing Time = 0.2708 (sec) and Critical Clearing Angle = 66.2984 (deg).

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CHAPTER 1: INTRODUCTION

1.1 Introduction

In 1882Alpha Edisonbuilt the first electric power system.It was a dc system. In 19th century next power system was built. It was dc system. Though the first reputation of dc systems by the turn of the 20th century ac systems in progress to outnumber them. The ac system was consideration to be greater as ac machines were cheaper than the dc counterparts and more significantly ac voltage is easily convertible from one level to another level by using transformer. The permanence problem of ac system was knowledgeable in 1920 when unsatisfactory clamming reason impulsive oscillations or chasing [1]. These troubles were resolved by means of generator restraint winding and turbine type key movers.

1.2 Stability in Power System

Permanence of a power system is facility to come back to standard or steady working situation after having been subjected to several figure of interruption. On the other hand, unsteadiness condition indicating synchronism loss or declining out of step. Moreover, permanence is the trend of power system to build up renovating forces same or better than forces in order to continue equilibrium state. It is called continue steady , if the forces nursing to grip machines in synchronism with one another are enough to defeat the troubling forces. It can reason spoil to the loads which obtain electric supply from the unstable system [2].

The permanence of a system refers to the capability to come back to its stable state when subjected to a trouble.By the synchronous generators, the power is generated. When voltage, frequency and phase sequence are same a generator is synchronized .

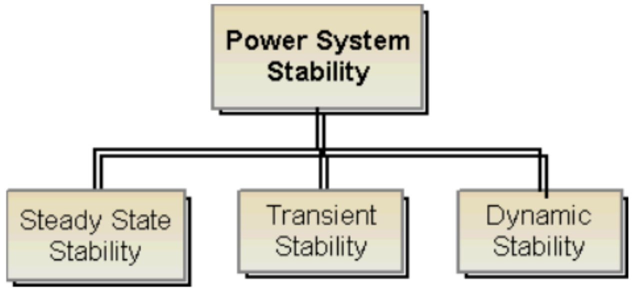


Figure 1-1 Power system stability

Steady state and the transient stability have given extra concentration its influence on the power system. Transient studies are required to make sure that the system can survive the transient condition following a main troublence.

Short circuit is a ruthless type of trouble. At the time of a fault, electrical power of near generators are reduced radically, whereas powers from remote generators are extremely affected. In some condition, the system may be steady even with continued fault; in other occurrences system will be constant only if the fault is cleaned with enough speediness. Fault depends on the location of fault, type of fault, clearing time.

Temporary permanence limit is lower than the steady state limit and here it is more essential. Temporary steadiness limit depends on the location, type of troublence and magnitude of troublence.

1.2.1 Steady State Stability Studies

Stable state steadiness is the capability of the system to increase restoring forces same or better than the troubling force and remain in equilibrium or synchronism after small and dawdling turbulence. Raise in load is a type of interruption. If raise in load takes place regularly and in little steps and the system resists this change and executes adequately, then the system is told to be in steady state stability. Thus the study of steady state stability is mainly concerned with the purpose of upper limit of machine's loading before losing synchronism, supplied the loading is amplified regularly at a slow rate. In practical, load vary may not be regular. System turbulences reason of:

a. unexpected load change

b. Switching function
c. generation loss
d. Fault

1.2.2 Dynamic Stability Studies

Dynamic steadiness is the capability of the power system to continue permanence under constant little turbulence also recognized as small-signal steadiness. These little turbulence happen due to random fluctuations in load and generation stages. Moreover this steadiness is capable to recover synchronism with addition of automatic control devices such as automatic voltage regulator (AVR) and frequency controls.

1.2.3 Transient Stability Studies

Transient stability is the capability of the power system to continue synchronism when suppress to strict temporary troublence as the incidence of a fault, the unexpected load shedding of a line or the unexpected application or cut of loads. The follow-on system reply occupies huge digressions of rotor angles of generators and inclined by the nonlinear power-angle liaison. Next unexpected turbulence , rotor speeds, rotor angular differences and power shift undergo fast changes whose magnitudes are dependent upon the strictness of turbulence. For a huge troublence, changes in angular differences may be so big as to reason the machine to fall. This kind of unsteadiness is known as Transient instability. Transient stability is a fast experience, typically happening within one second for a generator close to the reason of troublous. The object of the transient stability study is to determine if the load angle comeback to a stable value following the approval of the troublence[3].

The result of transmission line fault on synchronized generators is related to the transient stability studies. Transient instability incident is very swift and happens within one second or a fraction for generator shut to position of troublence.

At the time of fault, the generator power is reduced and the remote generator power is unchanged. The resulting variations in acceleration generate speed variations more than the time gap of the fault and essential to solve the fault quickly. The fault removes one or more transmission components and decline the system. If changes in transmission system create change generator rotor angles. If the changes accelerated machines raiseup extra load, they slow down and achieved new equilibrium situation. The synchronism loss will be clear within one second of the primary troublence.

Faults of seriously electrical lines are more instable than the unconscientiously loaded lines because they lean to generate extra acceleration at the time of fault. If the faults are not clear, produce extra angle differences in the neighborhood generators. Also, the backup fault clearing is executed after a time interruption and produces strict oscillations. The major load loss or a major generating station produces majortroublous in the system.

Causes of Transient:

Some of the more common causes of transients:

a. Atmospheric fact (lightning, solar flares, geomagnetic disturbances).
b. Switching loads on or off.
c. Disturbance of fault currents.
d. Power lines switching.
e. Capacitor banks switching.

1.3 Objective

In order to subject of the permanence problem, this project intends the examination of the transient stability of the power system using MATLAB. The goal of this work are:

a. To decide critical power angle, critical clearing times for circuit breaker, voltage level of the system and shift ability between systems for show whether system is steady or not.
b. To investigate bit by bit solution of the swing curve and equal area principle method by using MATLAB.
c. To investigate the condition of swift increases input power and three-phase fault on transmission line.

1.4 Project Scope

The possibilities to improvement this project includes of:

i. Focuses the methods;
   - Case 1: step by step solution of the swing curve
   - Case 2: the same region criterion on sudden raise the input power
   - Case 3: the same region criterion for a bus bar or line to line fault

ii. Propose a solution to overcome the faulted state from distribution system

1.5 Thesis Outlines

This chapter explains the importance of steadiness test of consecutive power flow for the power system. This chapter also explains introduction related and objective of this thesis.

Chapter 2 provides literature review on theoretical.

Chapter 3 explains the methodology analysis.

Chapter 4 explains the simulation and results analysis using MATLAB.

Chapter 5 explains conclusion about this thesis and future development plan.

CHAPTER 2: LITERATURE REVIEW

2.1 Transient Stability

Transient Stability is the capability of the power system to keep up in steadiness after huge and rapid turbulence. For example faults incidence, impulsive load changes, generating unit loss, line switching. Huge interruption happen on the system. These include strict lightning strikes, transmission line loss carrying largeness power due to overloading. The transient stability lessons grip the resolve of whether or not synchronism is maintained after the machine has been subjected to strict interruption [2]. Types of turbulences are [3]:

i) Impulsive load changing

ii) Generation loss

iii) System fault

Every generator operates at the same synchronous velocity and frequency 50 Hz as a slight balance between the input mechanical power and output electrical power is maintained. The frequency of system, falls when the generation is less than the actual load. On the another side the frequency of system rise whenever the generation is more than genuine load. [4].

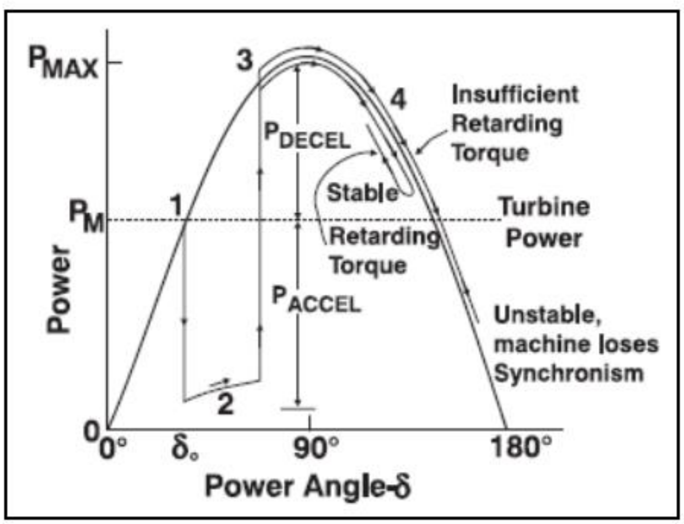
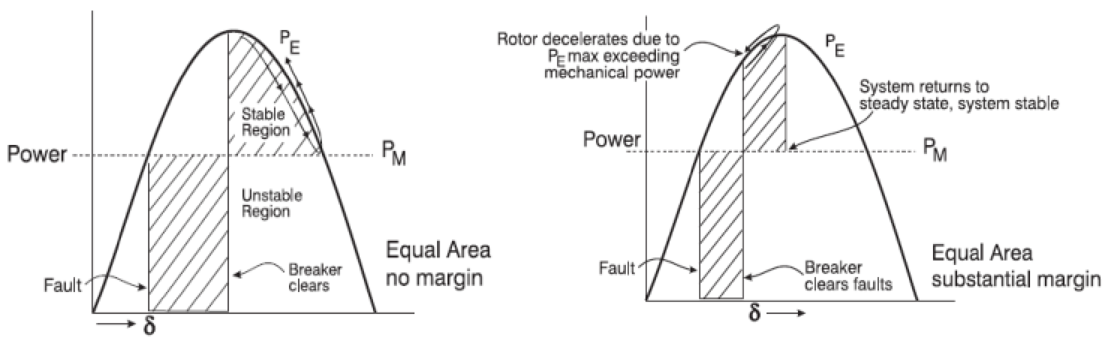


Figure 2-1 Transient Stability Illustration

Transient stability is first and foremost anxious with the instantaneous possessions of a transmission line troublous on synchronism of generator. Fig 2-1 demonstrates the characteristic activities of a generator in comeback to the faulty situation. Starting from the opening operating condition (point 1), a close-in transmission fault reasons the electrical output power P_e of generator to be significantly decreased. When the fault is solved, the electrical power is returned to a level parallel to the proper point on the power angle curve (point 3). Clearing the fault essentially eliminates one or more transmission fundamentals from service and at least provisionally weakens the transmission system. After fault clearing, the electrical power of the generator becomes larger than the mechanical power. This reasons the unit to decelerate (point 4), falling the momentum the rotor achieved at the time of fault.



(a) (b)

Figure 2-2 Effect of Fault Clearing Time

In the transmission system, power system permanence depends on the clearing time of fault. Slower fault clearing in Figure 2-2 (a), the curve of PE that the decelerating torque comes right to the limit of maintaining the rotor in synchronism. The shorter fault clearing time in Figure 2-2 (b) stops the acceleration of the rotor much faster.

2.1.1 Power Angle Curve

The current flowing in the transmission line is,

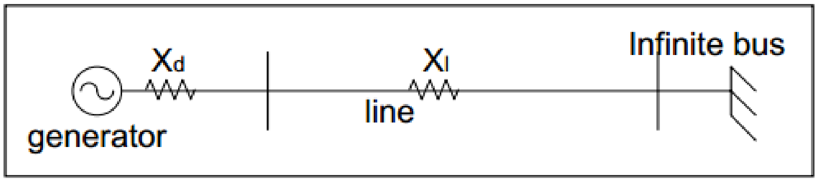


Figure 2-3 One Machine Infinite Bus

2.1.2 Transfer Reactance

Suppose that, before the fault, the power system is working at steady-state working condition. Temporary permanence problem of the power system is then defined as that of evaluating whether or not the system will arrive at a suitable steady-state working position following the fault.

2.1.3 Equal Area Criterion

The transient stability studies engage the purpose of whether or not synchronism is preserved after the machine has been subjected to separate troublence. It may be unexpected application of load, loss of huge load or fault or generation loss in the systemA process known as the equal-area criterion can be used for a rapid forecast of steadiness. This process is based on the graphical explanation of the energy stored in the rotating mass as an aid to decide if the machine maintains its stability after an interruption. The process is only applicable for a one-machine system or a two-machine system [4].

2.2 Review on the Stability of Power System

J.Tamura, and I.Taked [5]planned a latest technique for steady state permanence investigation of synchronous machine. Two steady-state permanence conditions were derived by assessing the value of a linearized edition of the latest swing equation, one was for step-out unsteadiness and the other for hunting. The author applied a latest system of steady state investigation to two types of synchronous machines, the normal synchronous machine and the doubly fed synchronous machine and argued its abilities. This system was developed by consider the damping torque. Though these two unsteadiness have generally been conversed separately so far, this new approach conversed two unsteadiness on a ordinary basis.

Armando Liamas and Jaime De La Ree [6] offered an item to analysis the theory of temporary energy and permanence. The author talk about the theory on the basic ideas which include the swing equation, stable and unstable equilibrium points and the same reason. Usually, power system studies the issue of transient permanence via the same region condition and step by step integration system. The reason of this object was to present a brief analysis of the same region measure and to begin a transient energy system for the one machine unlimited bus case. The object also explained a effortless interactive programme that plots the curve map of transient energy (up to the serious level) and at the time of fault and post fault trajectories.

Y.Dong and H.R.Pota [7] offered an expansion of the same region measure for multi-machine processes and applies it for resolve of the transient stability edge (TSM) of seriously troubled machines, for a given possibility, for real-time applications. This can be considered as a continuance of the transient stability evaluation which in general does not report the TSM quantitatively. The author prepared two practical contributions. First, it unlimited the well-known same region standard to around expect the transient stability edge and secondly recommended a easy process for performing the transient stability run, for varying load conditions, authenticate the results of the extended same region criterion. The transient stability system depends on the mechanical input of the dangerous machines and other situations build very small difference to the critical clearing angle. These two steps jointly form a very fast process of correctly determining the transient stability edge of a critical group of machine within a power system, for a given possibility and a given fault clearing time. Daiwa Okitsu, Tetsushi Miki, Yuuki Abe, Emi Takashima and MikiyaTano [8] have come with a result to develop the power transient stability evaluation by usingcritical fault clearing time function. This paper inspected the process to overcome the problems that simulation systems need too much calculation cost in order to contactcorrectly transient phenomena caused by faults of the power systems. The developed technique collected of 3 parts:

i) Assessment fault decision

ii) Critical fault clearing time function generation

iii) Average energy loss calculation

CHAPTER 3: METHODOLOGY

3.1 Transient Stability of an SMIB System

Transient constancy investigation of a power system is awide and difficultassignment. Though, it turns out that most of the vital facts and mechanisms can be captured by easy systems. In huge and difficult system it is frequently hard to differentiate the elemental and important facts from the more unrelated ones. It is significance to study easy systems to get close into and thoughtful of the basics, that may be used in the study of more difficult systems. Therefore, this chapter spotlight on transient steadiness of an SMIB system.

Suppose that Signal Machine Infinite Bus (SMIB) system shown in Figure 3.1

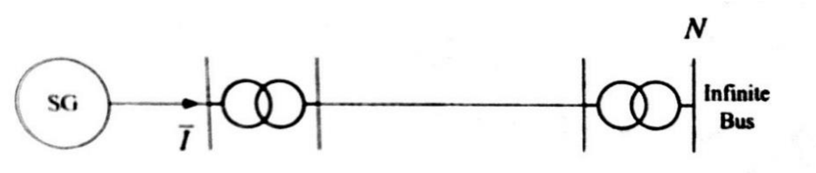


Figure 3-1 SMIB system

For the above SMIB system, the following assumptions are made:

1. The classical model is applied to the synchronous generator.
2. The system is losses and the transmission line is modeled by a series reactance.
3. Voltage and Current are symmetrical.
4. The mechanical power P_m is the constant.
5. The voltage at bus N is given by $\overline{U}_N = U_N < \theta_N$ where both $U_N$and θ_N are fixed.

Based on the above assumptions, we redraw the SMIB system in Figure 3.1 as shown in Figure 3.2, where x_{tot} is the sum of the reactance of the transmission line and the two transformers.

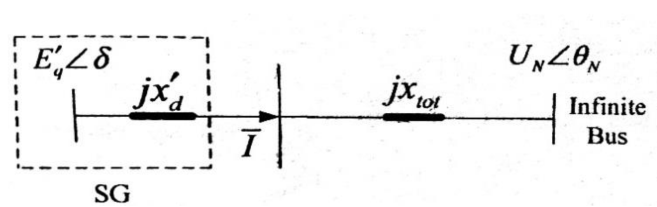


Figure 3-2 Proposed SMIB system for transient stability study

The dynamic of this system is given by the swing equation

$$\dot{\delta} = \omega$$
$$\dot{\omega} = \frac{1}{M}(P_m - P_e - D_\omega) \quad (3.1)$$

Where $P_e = \frac{E_q' U_N}{x_d' + x_{tot}} sin(\delta - \theta_N) = P_{emax}\, sin(\delta - \theta_N)$

3.1.1 Stability of the Equilibrium Points of the SMIB System

Stability of the equilibrium points $x_0 = x_s = \begin{bmatrix} x_{1,0} \\ x_{2,0} \end{bmatrix} = \begin{bmatrix} \delta_s \\ 0 \end{bmatrix}$ $and\ x_0 = x_u = \begin{bmatrix} x_{1,0} \\ x_{2,0} \end{bmatrix} = \begin{bmatrix} \delta_u \\ 0 \end{bmatrix}$ may be characteristics by a similar argumentation.

The Jacobeanat $x = x_0$ is given by

$$A = \begin{bmatrix} \frac{\partial f_1(x)}{\partial x_1} & \frac{\partial f_1(x)}{\partial x_2} \\ \frac{\partial f_2(x)}{\partial x_1} & \frac{\partial f_2(x)}{\partial x_2} \end{bmatrix}_{x=x_0} = \begin{bmatrix} 0 & 1 \\ -\frac{K}{M} & -\frac{D}{M} \end{bmatrix} \quad (3.2)$$

Where, $K = P_{emax}\cos(x_{1,0})$. The eigenvalues of (3.2) are given by

$$\lambda_{1,2} = -\frac{D}{M} \pm \sqrt{\left(\frac{D}{2M}\right)^2 - \frac{K}{M}} \quad (3.3)$$

By analogy with the solution, it can be shown that x_0 is asymptotically stable if $0 < x_{1,0} < \frac{\pi}{2}$. Therefore, $x_0 = x_s$ is asymptotically stable and $x_0 = x_u$ is unstable. Note that D is a positive small constant.

If there is no damping in the system (i.e. $D = 0$), then the given values are given by

$$\lambda_{1,2} = \pm\sqrt{-\frac{K}{M}} \quad (3.4)$$

By virtue of Appendix-2, it can be shown that $x_0 = x_u$ is unstable (show that).

However, Appendix-2 cannot characterize the stability of $x_0 = x_s$ when $D = 0$.

Therefore, Appendix-1 should be applied to characterize the stability of $x_0 = x_s$.

Using the energy function [11]

$$\mathcal{V}(x) = W_K + W_P = \frac{1}{2}M\omega^2 + \int_{\delta_s}^{\delta} (P_{emax}\sin(x_1) - P_m)dx_1$$

$$= \frac{1}{2}M\omega^2 - P_m(\delta - \delta_s) - P_{emax}(\cos(\delta) - \cos(\delta_s)) \quad (3.5)$$

$$= \frac{1}{2}M\omega^2 - P_m\delta - P_{emax}\cos(\delta) + C_0$$

It can be shown that $x_0 = x_s$ is stable if D = *0*. It can also be shown that $x_0 = x_s$ is asymptotically stable if $D \neq 0$. Note that in equation (4.8), $C_0 = P_m\delta_s + P_{emax}\cos(\delta_s)$is a constant such that $\mathcal{V}(x) = 0$. Henceforth, $x_s$will be denoted byx_0^s, and$x_u$byx_0^u.

Stability of $\delta_s$and δ_u may also be characterized as follows. Starting with δ_s(see Figure 3.3), assume that due to some disturbance δ moves from δ_s to δ_1 at which P_e is greater than P_m (and therefore$\dot{\omega} < 0$). This causes the generator to decelerate, and therefore the rotor angle δ starts to decrease and moves back toδ_s. Furthermore, the electric power P_e as a function of δ moves back toP_m. Next, assume that due to some disturbance δ moves from δ_s to δ_2 at which P_e is less than P_m (and therefore$\dot{\omega} > 0$). This reasons the generator to accelerate, and therefore the rotor angle δ starts to enlarge and moves back toδ_s. Also, P_e as a function of δ moves back to P_m. To summarize, when $\delta = \delta_1, P_e$ is greater thanP_m. Then the generator decelerates, and the rotor angleδ starts to decrease and moves back toδ_s. As δ passesδ_s. As δ passes δ_s again, P_e becomes greater thanP_m. Then the generator decelerates. However, due to the generator inertia (M or H) δ continues increasing and after a while it swings and moves back to δ_s. If there is no damping in the system, δ oscillates aroundδ_s. Therefore, δ_s is a stable e.p. (but not asymptotically stable). If there is damping in the system, then δ will be eventually be settled atδ_s. Therefore, the e.p. will be asymptotically stable.

Next consider δ_u. Assume that δ moves from this e.p to δ_3 at which $\dot{\omega} > 0$ (why?).

This causes the generator to accelerate, and the rotor angle δ increase and moves away from δ_u.

At $\delta = \delta_4$, the rotor angle δ decrease and moves away from δ_u(why?).

Therefore, this e.p. is unstable.

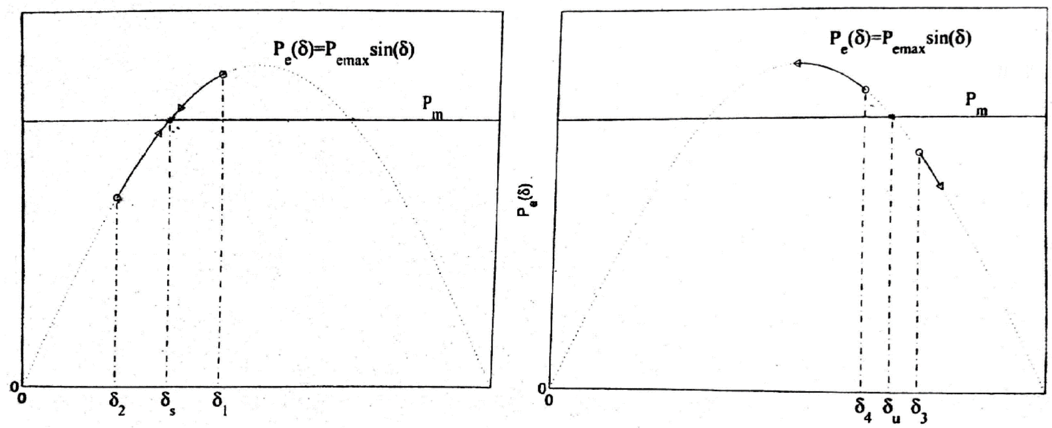


Figure 3-3 Stable and unstable equilibrium points

Up to now, the stability of the equilibrium points of the SMIB system was discussed. Next, the transient steadiness of the SMIB system will be discussed.

Due to the dynamic and structure of the swing equation, only transient stability is feasible in the SMIB system.

3.2 Equal Area Criterion (EAC)

A closer observation of Time vs Rotor Angle may lead to that the SMIB system is transiently stable (or first swing stable) if ω becomes zero. Since δ = ω the condition ω=0 implies that the rotor angle reaches a maximum, and then swing back (hence the name first-swing stability) as shown in Figure 3-4 for this casest_c =70 and t_c=100 (ms). This observation may be expressed as The SMIB system is that at some time (t_m), $\frac{d\delta}{dt}$ = ω(t_m) = 0.

Now, consider the swing equation

$$\dot{\omega} = \frac{d\omega}{dt} = \frac{1}{M}\left(P_m - P_e(\delta)\right)$$

Multiplying both sides of the swing equation by$\frac{d\delta}{dt}$= ω, the following is obtained

$$\omega\,\frac{d\omega}{dt} = \frac{1}{M}(P_m - P_e(\delta))\,\frac{d\delta}{dt} \qquad (3.6)$$

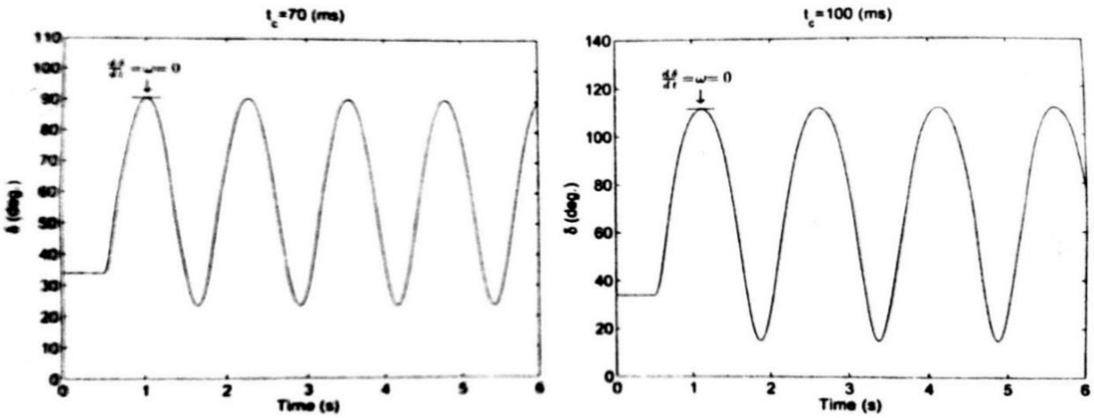


Figure 3-4 Variation of δ versus time

Integration of the (3.6) gives

$$\int_{0}^{\omega(t_m)} \omega \, d\omega = \frac{1}{M}\int_{\delta_s{}^{pre}}^{\delta_{max}} \left(P_m - P_e(\delta)\right) d\delta \qquad \Rightarrow$$

$$\frac{1}{2}\left(\omega(t_m)\right)^2 = \frac{1}{M}\int_{\delta_s{}^{pre}}^{\delta_{max}} \left(P_m - P_e(\delta)\right) d\delta \qquad \Rightarrow$$

$$\omega(t_m) = \sqrt{\frac{2}{M}\int_{\delta_s{}^{pre}}^{\delta_{max}} (P_m - P_e(\delta)) d\delta}$$

The stability condition is that $\omega(t_m)$ =0 which leads to

$$\int_{\delta_s{}^{pre}}^{\delta_{max}} (P_m - P_e(\delta)) d\delta = 0 \qquad (3.7)$$

The SMIB system is transiently stable if there be an angle $\delta = \delta_{max}$ such that equation (3.7) holds.

Let $\delta = \delta_c$ be clearing angle which corresponds to clearing time t_c. Then, equation (3.7) can be rewritten as

$$\int_{\delta_s{}^{pre}}^{\delta_{max}} (P_m - P_e{}^{f}) d\delta + \int_{\delta_c}^{\delta_{max}} \left(P_m - P_e{}^{post}\right) d\delta = 0$$

$$\int_{\delta_s{}^{pre}}^{\delta_c}(P_m - P_e{}^f)d\delta = \int_{\delta_c}^{\delta_{max}}\left(P_e{}^{post} - P_m\right)d\delta \qquad (3.8)$$

$$A_a = A_d$$

Where

$A_a = \int_{\delta_s{}^{pre}}^{\delta_c}(P_m - P_e{}^f)d\delta$ and $A_d = \int_{\delta_c}^{\delta_{max}}\left(P_e{}^{post} - P_m\right)d\delta$ (3.9)

Thus, the SMIB system is transiently stable if there be an angle $\delta = \delta_{max}$ such that $A_a = A_d$ (hence the name equal region criterion) as illustrated in Figure 3-5, (P^f is assumed zero).

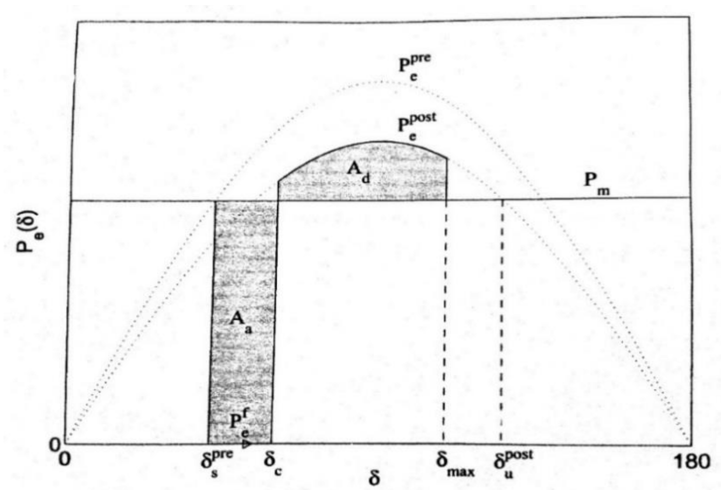


Figure 3-5 Equal area criterion (clearing angle δ_c).

But, what are A_a and A_d ? (or what do they represent?)

Consider again equation (3.14) which is rewritten as

$$\mathrm{M}\omega\frac{\mathrm{d}\omega}{\mathrm{dt}} = (\mathrm{P_m} - \mathrm{P_e}(\delta)\ \frac{\mathrm{d}\delta}{\mathrm{dt}}$$

Integrating the above equation, the following is obtain

$$\int M\omega\frac{d\omega}{dt} = \int (P_m - P_e(\delta)\ \frac{d\delta}{dt}$$

Where L.H.S $= \int_{\omega_1}^{\omega_2} \mathrm{M}\ \omega\ \frac{\mathrm{d}\omega}{\mathrm{dt}}\mathrm{dt} = \mathrm{M}\omega\ \mathrm{d}\omega = \frac{1}{2}\mathrm{M}[\omega^2]_{\omega_1}^{\omega_2}$

And R.H.S $= \int_{\delta_1}^{\delta_2}(P_m - P_e(\delta)\ \frac{d\delta}{dt}d\delta$

For $\delta_1 = \delta_s{}^{pre}$, $\delta_2 = \delta_c$, $\omega_1 = 0$ and $\omega_2 = \omega_c$, i.e. during the fault, we have

$$\text{L.H.S} = \frac{1}{M}({\omega_2}^2 - {\omega_1}^2) = \frac{1}{2}M{\omega_c}^2$$

$$\text{R.H.S} = \int_{\delta_1}^{\delta_2}(P_m - {P_e}^f)d\delta = \int_{\delta_1}^{\delta_2} P_m\, d\delta = P_m(\delta_c - {\delta_s}^{pre}) = A_a$$

$$A_a = \frac{1}{2}M{\omega_c}^2$$

That is

- $A_a$represents the kinetic energy injected into the system for the period of the fault. It is also called accelerating area.

In a similar way with$\delta_1 = \delta_c$,$\delta_2 = \delta_{max}$,$\omega_1 = \omega_c$ *and* $\omega_2 = \omega(t_m) = 0$ *and* $P_e = {P_e}^{post}$, it can be shown that.

- $A_d$represents the capability of the post-fault system to absorb energy, i.e. potential energy. It is also called decelerating area.

Setting,$\delta_{max} = {\delta_u}^{post}$,the maximum value of A_d is obtained which is denoted by A_{dmzx} as shown in Figure 3-6. Then,

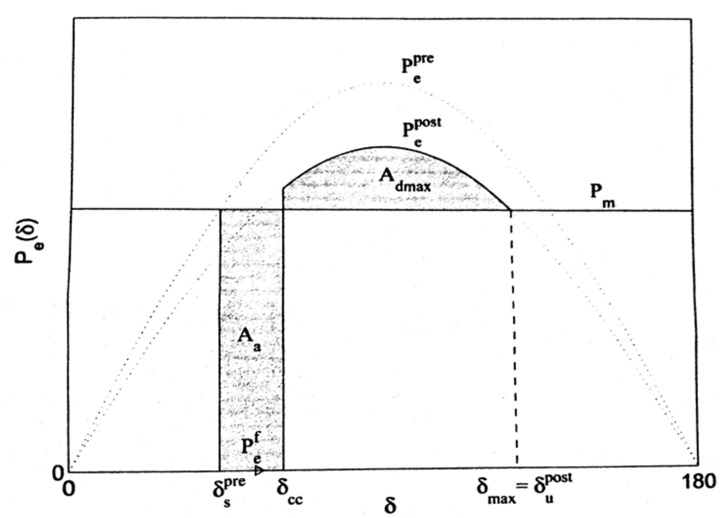


Figure 3-6 Equal area criterion (critical clearing angleδ_{cc})

- $A_a = A_{dmzx}$gives the critical angle δ_{cc}.
- The SMIB system is transiently stable if $A_a < A_{dmzx}$ $(or\ \delta_c < \delta_{cc})$.

In general, an SMIB system is transiently stable if $A_1 < A_2$ $(or\ \delta_c < \delta_{cc})$

Where, $A_1 = \int_{\delta_s{}^{pre}}^{\delta_c} (P_m - P_e{}^f) d\delta$

$A_2 = \int_{\delta_c}^{\delta_{max}} (P_e{}^{post} - P_m) d\delta$

With$\delta_{max} = \delta_u{}^{post}$. Furthermore, $A_1 = A_2$ gives δ_{cc}.

Consider the system and the x=case.

The critical angle δ_{cc} is given by $A_1 = A_2$ where

$$A_1 = \int_{\delta_s{}^{pre}}^{\delta_c} (P_m - P_e{}^f) d\delta = P_m[\delta]_{\delta_s{}^{pre}}^{\delta_{cc}} = P_m(\delta_c - \delta_s{}^{pre})$$

$$A_2 = \int_{\delta_c}^{\delta_{max}} (P_e{}^{post} - P_m) d\delta = \int_{\delta_c}^{\delta_{max}} [P_e{}^{post}\sin(\delta) - P_m]\, d\delta$$

$$= -P_e{}^{post}[\cos(\delta_{max}) - \cos(\delta_{cc})] - P_m(\delta_{max} - \delta_{cc})$$

$$A_1 = A_2 \Rightarrow \delta_{cc} = \arccos\left[\cos(\delta_{max}) + \frac{P_m}{P_{emax}^{post}}(\delta_{max} - \delta_s{}^{pre}\right] = 0.8192(rad.)$$

$$= 46.9370(deg.)$$

Since the electric power during the fault is constant ($P_e^f = 0$), the critical time t_{cc} can be obtained as follows.

During the fault, the dynamic of the system is given by

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

Since P_m/M is a positive constant, the system has a constant acceleration during the fault. The Critical Clearing Time t_{cc} can be gained by integrating the above equation twice. The first integration gives:

$$d\omega = \frac{P_m}{M}dt \qquad \Rightarrow \int d\omega = \int \frac{P_m}{M}dt \qquad \Rightarrow \omega = \frac{d\delta}{dt} = \frac{P_m}{M}t$$

The second integration gives:

$$\int_{\delta_s{}^{pre}}^{\delta_{cc}} d\delta = \int_{t=0}^{t=t_{cc}} \frac{P_m}{M} t dt \qquad \Rightarrow \qquad \delta_{cc} - \delta_s^{pre} = \frac{P_m}{2M} t_{cc}^2$$

Thus,

$$t_{cc} = \sqrt{\frac{2M}{P_m}(\delta_{cc} - \delta_s^{pre})} \quad \approx \quad 107.49(ms)$$

The system is stable for this fault if $t_c < t_{cc}$ as shown in Figure 3-7.

3.3 Transient Stability Enhancement

In this part, some of the common methods to develop the transient steadiness of power systems will be presented. For the purpose of illustration how the proposed methods enhance the transient stability, these methods will be applied to an SMIB system.

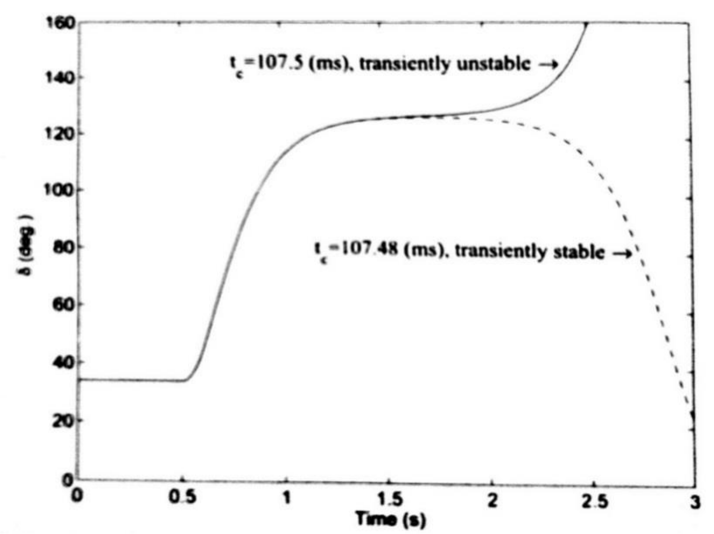


Figure 3-7 Critical clearing time $t_{cc} = 107.49\ (ms)$

However, it is to be noted that these methods are common, and can be applied to any real multi-machine power system.

In previous section, it has been shown that the SMIB system is transiently steady for a given fault and a given clearing time t_c, if $t_c < t_{cc}\ or\ (A_1 < A_2)$. Using this relationship, a stability measure may be defined as follows

$$\mathcal{M}_t = \frac{t_{cc} - t_c}{t_{cc}} 100\% = \left(1 - \frac{t_c}{t_{cc}}\right) 100\% \tag{3.10}$$

$$\mathcal{M}_A = \frac{A_2 - A_1}{A_2} 100\% = \left(1 - \frac{A_1}{A_2}\right) 100\% \tag{3.11}$$

Shunt capacitor compensation

The major function of shunt capacitor return to keep the voltage profile of the (heavily loaded) transmission system within acceptable levels (i.e. close to the nominal value). This compensation also increases the maximum power transfer capability which results in enlargement of A_2.

Let a shunt capacitor with B = 0.52 (p.u) be installed at bus 3 to keep the steady-state voltage magnitude of this bus at 1 (p.u). Thus, by this compensation $t_{cc}^{new} = 0.1505$(s), and $M_{txc} = 33.5329\%$

Obviously, compared to the shunt capacitor, compensation, the braking resistors and series capacitor compensation are more effective of achieving transient stability enhancement.

3.4 Load Modeling

As presented in [12] the term “load” can have some implications. In this compendium the following definition of the load is however of concern.

- “A part of the system that is not clearly represented in a system model, but fairly is treated as if it were single power-consuming power device connected to a bus in the system model” [12]

Based on this definition, the load at a (high voltage) bus signifies the total amount of hundreds or thousands of individual commercial, industrial and residential power-consuming devices such as motors, heating, lighting and electrical machines as shown in Figure 3-8.

This total load model represented by static or dynamic load form, or a combination of both as expressed in (3.12)

$$\overline{S_L} = k\overline{S_{st}} + (1-k)\overline{S_{dyn}} \text{where} \quad 0 \le k \le 1 \tag{3.12}$$

Where 'k' is the fraction of the load represented by static load model. $\overline{S_L} = \overline{U_L}\overline{I_L^*} = P_L + jQ_L$is a mathematical representation of the combined load model. It gives the correlation between current flowing and bus voltage into the (composite) load.

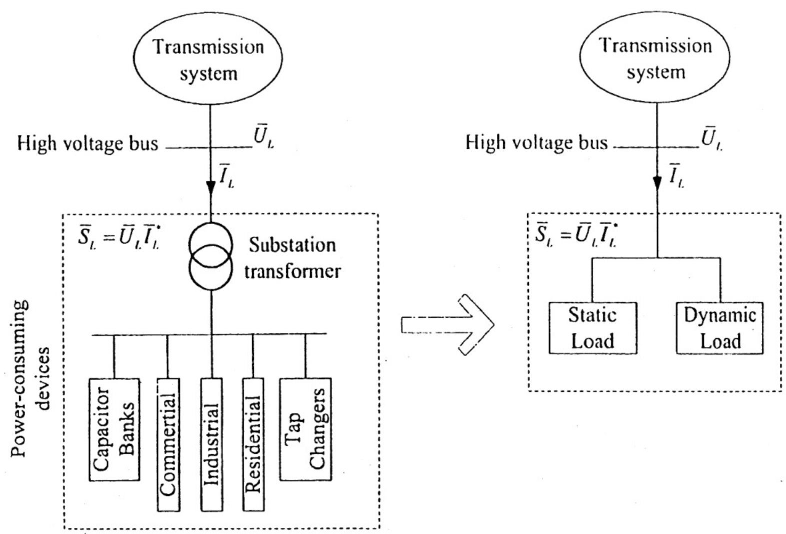


Figure 3-8 A composite load model for representing physical loads.

3.4.1 Static Load Model

This model states the character of load at any instant of time as functions of the frequency at the same instant and bus voltage magnitude [12]

The ZIP and exponential models are two types of the static load models which have been broadly used to represent the voltage dependency of loads.

In exponential model, active and reactive components of the load are expressed as (it is assumed that k = 1, i.e. $P_L = P_{st}$and $Q_L = Q_{st}$)

$$P_L = P_{EXP} = P_{Lo}\left(\frac{U_L}{U_{Lo}}\right)^{mp} \text{ and } Q_L = Q_{EXP} = Q_{Lo}\left(\frac{U_L}{U_{Lo}}\right)^{mq} \quad (3.13)$$

- With *mp* = *mq* = 0, the model describes constant power attribute.
- With *mp* = *mq* = 1, the model describes constant current attribute.
- With *mp* = *mq* = 2, the model describes constant impedance attribute.

Based on the nature of the composite load characteristics at a given bus these exponents may have different values.

In the model of ZIP, active and reactive components of the load are described as

$$P_L = P_{ZIP} = P_{Lo}\left[k_{pz}\left(\frac{U_L}{U_{L0}}\right)^2 + k_{pi}\left(\frac{U_L}{U_{L0}}\right) + k_{pp}\right]$$

$$Q_L = Q_{ZIP} = Q_{Lo}\left[k_{qz}\left(\frac{U_L}{U_{L0}}\right)^2 + k_{qi}\left(\frac{U_L}{U_{L0}}\right) + k_{qp}\right] \quad (3.14)$$

This model is created of constant impedance (Z), constant current (I), and constant power (P) components. The parameters $k_p$and $k_q$describe the fraction of each component. Note that $k_{pz} + k_{pi} + k_{pp} = k_{qz} + k_{qi} + k_{qp} = 1,$

A more general illustration of the static loads is given by (3.15) where the frequency dependency of load features are included [13]-[14].

$$P_L = P_{ZIP} + kP_{Lo}\left(\sum_{k=1}^{2} k_{pk}\left(\frac{U_L}{U_{L0}}\right)^{mpk}(1 + D_{pk}\Delta f\right)$$

$$Q_L = Q_{ZIP} + kQ_{Lo}\left(\sum_{k=1}^{2} k_{qk}\left(\frac{U_L}{U_{L0}}\right)^{mqk}(1 + D_{qk}\Delta f\right) \quad (3.15)$$

Where D_{pk} and D_{qk} are damping constants, and $\Delta f = f - f_s$ is the bus frequency deviation (f is the actual frequency of the bus, and f_s is the nominal frequency of the bus). It is obvious that the load models (3.13)-(3.14) are derivatives of the general model (3.15) in which$k_{pz} + k_{pi} + k_{pp} + k_{p1} + k_{p2} = k_{qz} + k_{qi} + k_{qp} + k_{q1} + k_{q2} = 1$.

3.4.2 Dynamic Load Model

It is known that load characteristics have an important impact on power system dynamics. Therefore, accurate load modeling is vitally important for power system utilities to predict more precisely the power system operating limits and stability margins. Thus, in many steadiness learns such as voltage stability and long term steadiness.

Electrical motors consume a big amount of total electrical energy provided by a power system and a big number of motors are induction motors which involve damping of oscillations. Thus, in addition to studies of long-term stability and voltage stability, for improving damping prediction it has also been recommended that major blocks of induction motor load should be represented by dynamic models including both inertial and rotor flux dynamics (known as third-order model) [12]-[14]. For an induction machine the favored reference frame is one with the axes rotating at synchronous speed ,i.e. the stator and rotor quantities are transferred to a reference frame which turns at synchronous speed ω_s.

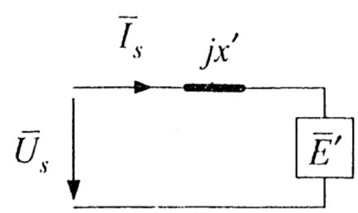


Figure 3-9 Induction motor transient-equivalent circuit (third-order model).

In Figure 3.9,$x'$is the transient reactance , and based on dq-components of the new reference frame we have the following :

$$\overline{U_s} = U_q + jU_d$$

$$\overline{I_s} = I_q + jI_d$$

$$\overline{E'} = E_q + jE_d$$

Moreover, from the figure the following can be obtained

$$I_q = \frac{U_d - E'_d}{x'} \quad \text{and} \quad I_d = \frac{U_q - E'_q}{x'} \tag{3.16}$$

Let x_m be the magnetizing reactance, r_r be the rotor resistance, and x_s and x_r be the leakage reactance's of the stator and the rotor, respectively. Then, it can be shown that based on the *dq*-components of the new reference frame the dynamic of this induction motor is given by [18].

$$\dot{s} = \frac{1}{2H}(T_m - T_e)$$

$$\begin{aligned} \dot{E}'_q &= \omega_s s E'_d - \frac{1}{T'_0}(E'_q + (x - x')I_d) \\ \dot{E}'_d &= \omega_s s E'_q - \frac{1}{T'_0}(E'_d + (x - x')I_q) \end{aligned} \tag{3.17}$$

Where,

$s = \frac{\omega_s - \omega_{motor}}{\omega_s}$ is the slip of the induction motor

$T_m = A+Bs+Cs^2$ is the mechanical load torque in terms of the slip

$T_e = E'_q I_q + E'_d I_d$ is the electrical torque

$T'_0 = \frac{x_r + x_m}{\omega_r r_r}$ (the transient open-circuit time constant)

$x' = x_s + \frac{x_m x_r}{x_m + x_r}$ and $x = x_s + x_m$

Note that I_q and I_d in (3.17) are given by (3.16). Furthermore, $\overline{U_L} = \overline{U_s}$ and if $k = 0$ we have $\overline{I_L} = \overline{I_s}$, $\quad i.e. \quad \overline{S_L} = \overline{S_{dyn}}$.

There are also other dynamic load models which are summarized in [14].

3.5 Multi-machine Power Systems

Fig 3-10 shows a multi-machine power system. The transmission network has a total *N* buses in which the first *n* are generators terminal buses. Voltages at these buses are given by *U*.

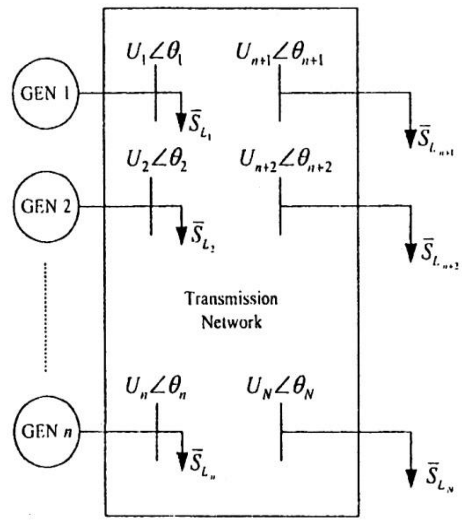


Figure 3-10 A multi-machine power system.

For this system the following assumptions are made:

- Dynamic of each generator is explained by the one-axis model.
- Mechanical power of each one generator (i.e. P_m) is constant.
- Inherent damping of each generator (i.e. D) is zero.
- Transmission network is lossless.

Based on the assumption 1, the equivalent circuit of the k^{th}generator is shown in Fig 3-11 where the reactance of the k^{th} transformer is included in x'_{dk}. The voltage at the generator internal bus is given by $E'_{qk}\angle\delta_k$.

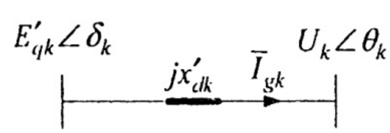


Figure 3-11 Synchronous generator one-axis dynamic circuit

3.5.1 Structure Preserving Model

Based on the assumptions 1-3, the dynamic of the k^{th} generator is given by

For$k$ = 1 ....n

$$\dot{\delta}_k = \omega_k$$

$$\dot{\omega_k} = \frac{1}{M_k}\left(P_{mk} - \frac{E'_{qk}U_k}{x'_{dk}}\sin(\delta_k - \theta_k)\right) \tag{3.18}$$

$$E'_{qk} = \frac{1}{T'_{dok}}\left(E_{fk} - \frac{x_{dk}}{x'_{dk}}E'_{qk} + \frac{x_{dk} - x'_{dk}}{x'_{dk}}U_k\cos(\delta_k - \theta_k)\right)$$

Where reactance of the k^{th} transformer is also included in x_{dk}.

Next, let $Y_{bus}$of order (NN) be the admittance matrix often transmission network, and the klth element of the admittance matrix defined by $\bar{Y}_{buskl} = G_{kl} + jB_{kl}$ where G_{kl} represents only the resistances of the relevant transmission lines. However, based on the assumption 5 (since $R \ll X$)$G_{kl} = 0$, and therefore $\bar{Y}_{buskl} = jB_{kl}$.

The real and reactive powers injected into bus k are given by

For$k = 1 ... n$

$$P_k = \sum_{l=1}^{N} B_{kl}U_kU_l\sin(\theta_k - \theta_l) + \frac{E'_{qk}U_k\sin(\theta_k - \delta_k)}{x'_{dk}} \tag{3.19}$$

$$Q_k = -\sum_{l=1}^{N} B_{kl}U_kU_l\cos(\theta_k - \theta_l) + \frac{U_k^2 - E'_{qk}U_k\cos(\theta_k - \delta_k)}{x'_{dk}}$$

and for $k = (n+1) ... N$

$$P_k = \sum_{l=1}^{N} B_{kl}\, U_k U_l \sin(\theta_k - \theta_l)$$
$$(3.20)$$
$$Q_k = -\sum_{l=1}^{N} B_{kl}\, U_k U_l \cos(\theta_k - \theta_l)$$

Let P_{Lk} and Q_{Lk} be the active and reactive loads at bus k. Then, for k = 1 … N the power flow equations (3.19) and (3.20) may be written as

$$P_k + P_{Lk} = 0 \qquad (3.21)$$
$$Q_k + Q_{Lk} = 0$$

Which is a set of algebraic equations.

Let

$$x = \left[\delta_1 \dots \delta_n, \omega_1 \dots \omega_n, E'_{q1} \dots E'_{qn}\right]^T$$
$$y = [\theta_1 \dots \theta_N, U_1 \dots U_N]^T \qquad (3.22)$$

Then, equations (3.18) and (3.21) can be rewritten as

$$\dot{x} = f(x, y) \qquad (3.23)$$
$$0 = g(x, y)$$

Equation (3.23) is a set of differential algebraic equations which is described the dynamic of the multi-machine system.

3.5.2 Reduced Network Model

The (RNM) can be obtained by replacing 4 assumption with the following assumption.

Loads are represented as constant impedances, $\bar{Z}_{L_k} = R_{L_k} + jX_{L_k} = \frac{U_k^2}{P_{L_k} - jQ_{L_k}}$.

Impedance loads can also be given in the form of admittance loads as

$$\bar{y}_{L_k} = \frac{1}{\bar{Z}_{L_k}} = \frac{P_{L_k} - jQ_{L_k}}{U_k^2} \tag{3.24}$$

Let Y is the order of (N×N) be the admittance matrix of transmission network in which the admittance loads are included, $i.e.\, Y = Y_{bus} + Y_L$, where Y_L is a diagonal matrix of order N×N whose diagonal entries are$\bar{y}_{L_k}$. Then, the *kl-th*element of admittance matrix is given by $\bar{Y}_{kl} = G_{kl} + jB_{kl,}$ where $jB_{kl} = 0$ for k $\neq l$ due to assumption 5. However $G_{kk} \neq 0$ because of the admittance loads.

Next, the multi-machine system is augmented with n buses which represent the generators buses as shown in Figure 3.12*i.e.*the total number of buses is n+N.

The current of the *k-th*generator *(i.e.* $\bar{I}_{gk}$*)* is given by

$$\bar{I}_{gk} = \frac{\overline{E'_{qk}}_{qk} - \bar{U}_k}{jx'_{dk}} \text{for } k = 1 \dots\dots n \tag{3.25}$$

By the Kirchhoff's current law,

$$0 = \sum_{l=1}^{N} \bar{Y}_{kl}\bar{U}_l - \bar{I}_{gk} for\ k\ =\ 1 \dots .n \tag{3.26}$$

$$0 = \sum_{l=1}^{N} \bar{Y}_{kl}\bar{U}_l\, for\ k\ =\ n+1 \dots ..N \tag{3.27}$$

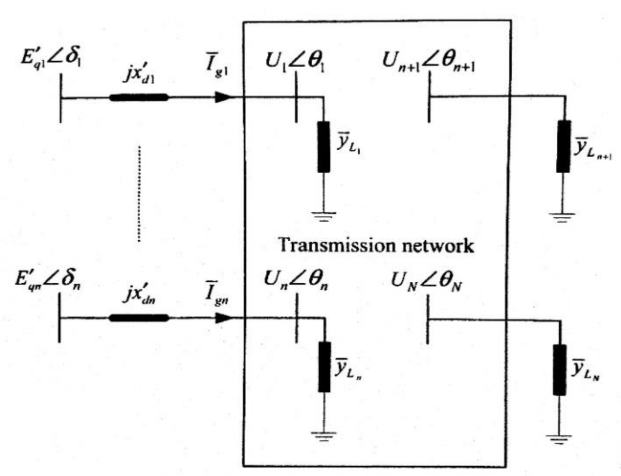


Figure 3-12 Augmented multi-machine power system.

Or in compact form

$$\begin{bmatrix} I_G \\ 0_N \end{bmatrix} = \begin{bmatrix} Y_A \ Y_B \\ Y_C \ Y_D \end{bmatrix} \begin{bmatrix} E_G \\ U_N \end{bmatrix} \tag{3.28}$$

Where,

- $I_G = \left[\bar{I}_{g1} \ldots\ldots \bar{I}_{gn}\right]^T$, and 0_N is a zero vector order $N \times 1$.
- $E_G = \left[\bar{E}'_{q1} \ldots. \bar{E}'_{qn}\right]^T$, and $U_N = [\bar{U}_1 \ldots\ldots \bar{U}_N]^T$.
- Y_A is the diagonal matrix of order n×n whose diagonal entries are $\bar{Y}_{A_{kk}} = \frac{1}{jx'_{dk}}$.
- Y_B is a zero matrix of order n×N whose non-zero entries are $\bar{Y}_{B_{kk}} = \frac{-1}{jx'_{dk}}$.
- $Y_C = (Y_B)^T$.
- Y_D is a matrix of order N×N which is given by $Y_D = Y + \begin{bmatrix} Y_A \ 0_1 \\ 0_2 \ 0_3 \end{bmatrix}$.

Equation (3.28) can be rewritten as,

$$I_G = Y_A E_G + Y_B U_N \tag{3.29}$$

$$0_N = Y_C E_G + Y_D U_N \tag{3.30}$$

By solving U_N from equation (3.30), and substituting it in equation (3.29), the following is obtained

$$U_N = -Y_D^{-1} Y_C E_G$$

$$\begin{aligned} I_G &= Y_A E_G + Y_B U_N = (Y_A - Y_B Y_D^{-1} Y_C) E_G \\ &= Y_{RNM} E_G = (G + jB) E_G \end{aligned} \tag{3.31}$$

Thus *k= 1……n*

$$\bar{I}_{gk} = (G_{kk} + jB_{kk})\bar{E}'_{qk} + \sum_{\substack{l=1 \\ l \neq k}}^{n} (G_{kl} + jB_{kl})\bar{E}'_{ql} \tag{3.32}$$

Where,

- $Y_{RNM} = G + jB$ is the admittance matrix of the diminished network model which is the order n×n.

- G_{kk}andB_{kk} represent the equivalent short-circuit conductance and susceptance of the *k-th* generator.
- G_{kl}andB_{kl} represent the transfer conductance and susceptance between internal busses *k* and *l*.

Note that $G_{kk}\ and\ G_{kl}$ are non-zero in case of having any active load in the system *i.e.*$P_L \neq 0$.
The generator current $\bar{I}_{gk}$ can be written as

$$\bar{I}_{gk} = \left(I_{qk} + jI_{dk}\right)e^{j\delta_k}$$
$$= (G_{kk} + jB_{kk})E'_{qk}e^{j\delta_k} + \sum_{\substack{l=1\\ l\neq k}}^{n}(G_{kl} + jB_{kl})E'_{ql}e^{j\delta_l} \qquad (3.33)$$

From which I_{qk} and I_{dk} can be solved for k = 1………..n, as

$$I_{qk} = G_{kk}E'_{qk} + \sum_{\substack{l=1\\ l\neq k}}^{n} E'_{ql}\left(G_{kl}\cos(\delta_k - \delta_l) + B_{kl}\sin(\delta_k - \delta_l)\right)$$
$$(3.34)$$
$$I_{dk} = B_{kk}E'_{qk} + \sum_{\substack{l=1\\ l\neq k}}^{n} E'_{ql}\left(B_{kl}\cos(\delta_k - \delta_l) - G_{kl}\sin(\delta_k - \delta_l)\right)$$

Based on equations, the dynamic of the *k-th* generator is given by

$$\dot{\delta}_k = \omega_k$$
$$\dot{\omega}_k = \frac{1}{M_k}(P_{mk} - P_{ek}) = \frac{1}{M_k}(P_{mk} - E'_{qk}I_{qk}) \qquad (3.35)$$
$$\dot{E}'_{qk} = \frac{1}{T'_{dok}}(E_{fk} - E'_{qk} + (x_{dk} - x'_{dk})I_{dk})$$

Substituting (3.34) into (3.35), the following is obtained

$$\dot{\delta}_k = \omega_k$$
$$\dot{\omega}_k = \frac{1}{M_k}\left[P_{mk} - G_{kk}E'^2_{qk} - \sum_{\substack{l=1\\ l\neq k}}^{n} E'_{qk}\,E'_{ql}(G_{kl}\cos(\delta_{kl}) + B_{kl}\sin(\delta_{kl}))\right]$$

$$\dot{E}'_{qk} = \frac{1}{T'_{dok}}\left[(E_{fk} - E'_{qk} + (x_{dk} - x'_{dk})\left(B_{kk}E'_{qk} + \sum_{\substack{l=1 \\ l\neq k}}^{n} E'_{ql}(B_{kl}\cos(\delta_{kl}) - G_{kl}\sin(\delta_{kl}))\right)\right] \tag{3.36}$$

Where $\delta_{kl} = \delta_k - \delta_l$

It is obvious that (3.36) contains only state variables and constants. The reason is that with the loads represented by constant impedances all N network buses are eliminated by equation (3.31), and there are no algebraic variables (i.e. the voltages at the network buses) in (3.36).Therefor, there is no need of (3.21) to calculate the algebraic variables y.

Using x in (3.22) and equation (3.36) can be written as

$$\dot{x} = f(x) \tag{3.37}$$

i.e. the dynamic of the multi-machine system shown in figure 3.12 is expressed by only a set of differential equations. Furthermore the $(n+N)$-bus system in figure 3.12 is reduced to an n-bus system.

3.6 Rotor Angle Stability

Small-signal stability which is anxious with the capability of the power system is to keep synchronism under little turbulence. The turbulence are considered to be adequately little that linearization of system equation is allowable for purpose of investigation.

3.6.1 Transient Stability

The main aim of transient stability investigation of a power system is to study whether the system after a large disturbance will settle to an acceptable steady-state as time passes. To ensure power system stability (or security), power system utilities would like to assess the performance either current or postulated power system configuration under a variety of actual or hypothesized operating situation and turbulence. Then the results of the stability studies, they take preventing control action if necessary.

For transient stability study, power system utilities broadly apply time domain simulation programs to forecast the response of the system to different large turbulence. In these programs, the dynamic of the system can be explained by a set of differential algebraic equation of the form (3.23) (or only differential equation) which are answered by using gradually numerical integration methods. By the simulation results, the performance of the system is evaluated to predict the system stability and operating limits. An advantages of applying time-domain simulations is that it is possible to have more detailed models for generators and other power system components. By these detailed models, the dynamic behaviors of the actual power system mechanism are then more accurately represented.

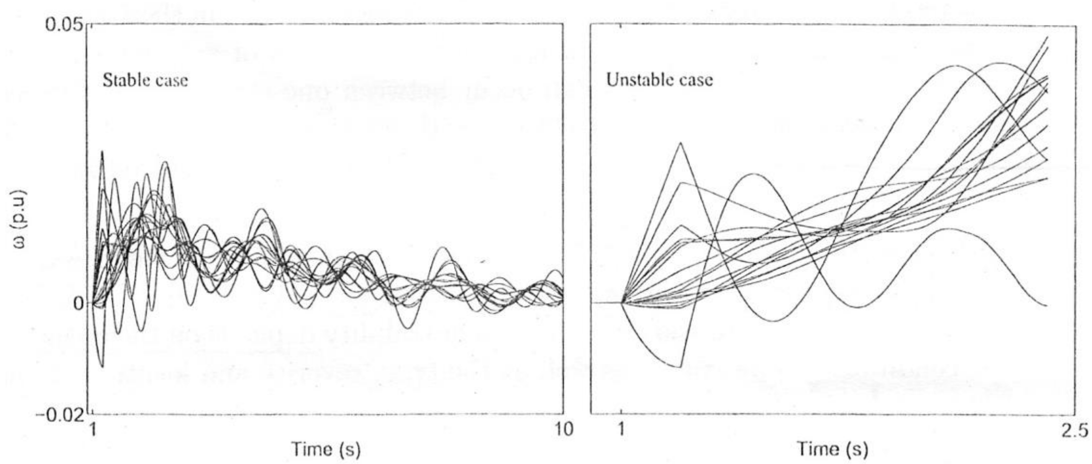


Figure 3-13 Speed deviation of each generator

Figure 3-13 shows dynamic behaviors of the generators in the Nordic32 test system proposed by CIGRE after a large disturbance for different clearing times. For the unstable case, the system loses its synchronism and it is transiently unstable for the specified disturbance and clearing time. Simulation were performed by using the summation program SIMPOW, and the results were plotted in MATLAB.

The time-domain approach has however disadvantages such as heavy and time-consuming computations (especially for large interconnected power systems). Moreover (as shown in the above figure), it does not offer any information regarding the stability margin.

To overcome these advantages, other transient stability analysis methods have been developed .

3.6.1.1 Single Machine Equivalent (SIME) Method

The SIME method is a mixture direct-temporal transient stability system, which convert the lines of a multi-machine power system into the line of a single machine equal system of the form

$$\dot{\delta_{SMIE}} = \omega_{SMIE}$$
$$\dot{\omega_{SIME}} = M^{-1}[P_{mSIME} - P_{eSIME}] \tag{3.38}$$

Whose parameters (which are derived from multi-machine power system) are time changeable [15].

Mainly, the SIME technique treaties with the post fault pattern of a power system subjected to interruption which most probably obliges to unsteadiness. In that form, the SMIE technique applies a time domain programme in order to recognize the form of partition of that's machines are two groups, that is Critical (subscript *C*) and Non-critical Machine (subscript *N*) which are substituted by sequentially a two machine equal. Then, two-machine equivalent is returned by a single machine equivalent system. By description, the critical machines are the machine that dependable of the loss of synchronism.

The parameters of (3.38) are given by

$$\delta_{SIME} = \delta_C - \delta_N$$
$$\omega_{SIME} = \omega_C - \omega_N$$
$$P_{mSIME} = M_T^{-1}\left(M_C \sum_{i \in C} P_{mi} - M_N \sum_{j \in N} P_{mj}\right)$$
$$P_{eSIME} = M_T^{-1}\left(M_C \sum_{i \in C} P_{ei} - M_N \sum_{j \in N} P_{ej}\right)$$

$$M = \frac{M_C M_N}{M_T} \qquad and \qquad M_T = M_C + M_N$$

Where

$$M_C = \sum_{i \in C} M_i \qquad , \qquad M_N = \sum_{j \in N} M_j$$

$$\delta_C = M_C^{-1} \sum_{i \in C} M_i \, \delta_i \qquad , \qquad \delta_N = M_N^{-1} \sum_{j \in N} M_j \, \delta_j$$

$$\omega_C = M_C^{-1} \sum_{i \in C} M_i \, \omega_i \qquad , \qquad \omega_N = M_N^{-1} \sum_{j \in N} M_j \, \omega_j$$

By refreshing the parameters of the single machine equivalent system at each one integration time-step and numerically assessing the transient steadiness of this equivalent system stands on the same area condition, the SMIE method provides accurate and fast transient steadiness evaluation of multi-machine power systems, and also supplementary interesting information that is stability borders, classification of the type of unsteadiness and equivalent critical machines, sensitivity investigation and control systems [15]-[16].

3.7 Excitation System Integration with One-axis Model

The principal function of an exciter is to supply a dc source for a synchronous generator's field excitation, and the AVR controls the excited voltage. Control on excitation voltage is controlling the field current (i.e. i_f in figure, or E_f in equation (3.36)) which in rotate controls the reactive power and produced voltage. This act contributes to the enhancement of system steadiness.

In general, 2 kinds of exciters - static exciters and rotating. The rotating exciters make use of either ac generators or dc generators with rectifiers as sources to supply dc current to the generator's field winding. Figure 3.14 illustrates basic structure of the excitation system with rotating exciters.

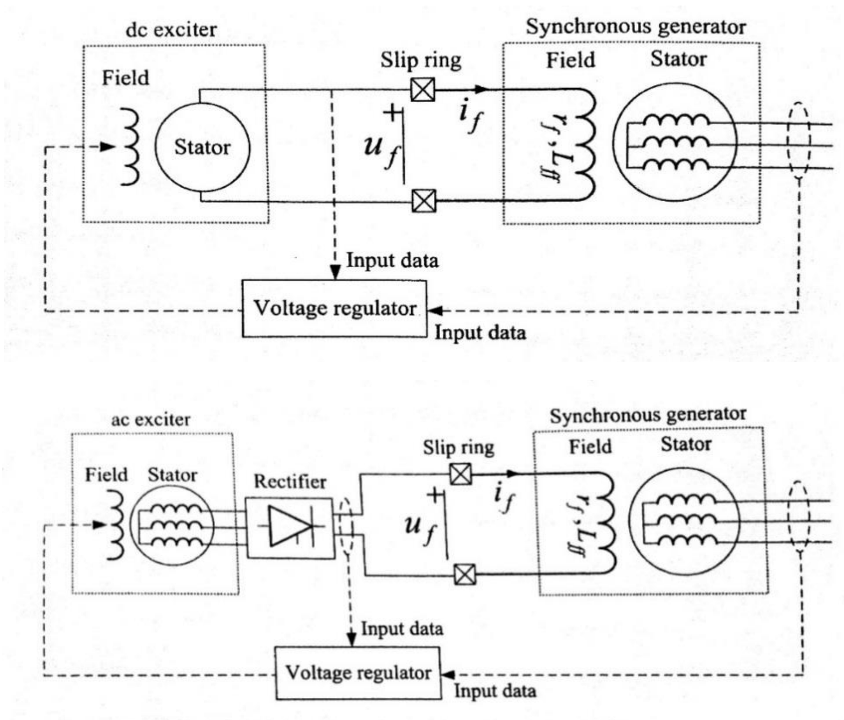


Figure 3-14 Basic structure of the excitation systems with rotating exciters.

DC exciter: A dc exciter can be drive by the shaft or a motor of the generator. It supplies the dc current to the field winding of the synchronous generators through slip rings. These excitation systems belong to early systems. Due to their obsolescence, and also the needs of today's power systems to high speed excitation systems on the every grid connected generating units with high-field forcing ability , many older dc exciters are being replaced by ac or static type systems.

AC exciter: In ac excitation scheme, the output of ac is rectified and to supply the dc current essential by the field winding of the synchronous generator. If the rectifier is stationary slip rings will be needed. With rotating rectifiers, the need for slip rings is however eliminated.

STARIC: Figure 3.15 shows the basic structure of static excitation systems. The rectifiers are honestly fed from the terminals of generator via a step down transformer to supply dc current requisite by the field winding of the synchronous generator. In these excitation system, slip ring are needed, and the rectifiers are controlled openly by voltage regulator. By far, most excitations systems installed nowadays are of this type.

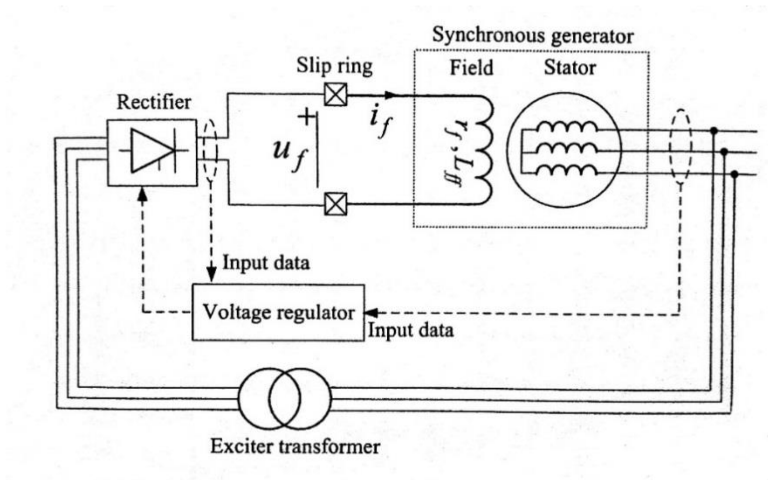


Figure 3-15 Basic structure of static excitation systems.

As mentioned before, the above figure only illustrate the basic structure of these different type of excitation systems. Easy type has however different configurations which are comprehensively described in [17], and related references therein.

Fig: 3.16 illustrates the block diagram of a simple excitations method which will be used in this compendium (especially for small signal analysis).

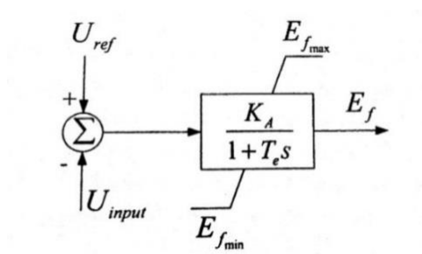


Figure 3-16 Block diagram of a simple excitation system.

In the figure T_e and$K_A$represent the time constant of exciter and the gain of an amplifier respectively. Further, U_{ref} is the set value and $U_{input}$is the voltage which will be controlled. $U_{input}$is indeed the output of the block diagram as shown in figure 3.17, where $\overline{U}$ is the voltage of generator terminal, $\overline{I}$ is the current, and $U = |\overline{U}|$.

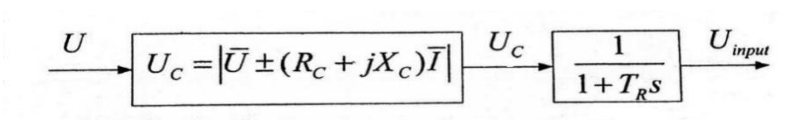


Figure 3-17 Block diagram of load compensation and transducer.

The first block is known as load compensator and $\overline{Z_C} = R_C + jX_C \approx jX_C$ is known as compensator impedance. If the generator terminal voltage will be controlled, then $\overline{Z_C} = 0$ that is $U_C = U$. Though, if the voltage at a point beyond the generator terminal will be restricted, then $\overline{Z_C} \neq 0$ which represents the electrical distance between the point and the generator terminal. The negative sign represent the point at which the voltage will be restricted is closer to the transmission system. By this compensation, the voltage at an (artificial) point within each generator will be restricted that results in a stable and adequate reactive power productions between the generators. The second block is known as transducer which represent the delay due to measuring, filtering and rectifying of the signal. $T_R$is usually very small, and this block can therefore be omitted. In this compendium, the load compensation is also omitted since the control of the terminal voltage is of concern that is$U_{input} = U$.

It will be exposed that excitation method among high gain will introduce very reduced or negative damping in electromechanical oscillations that can guide to angular unsteadiness. To eliminate this effect and progress the system damping in general, a supplementary damping device known as power system stability (PSS) is added to the excitation system. This device supplies an additional supplementary signal to the voltage regulator at the summing junction as Figure 3.18.

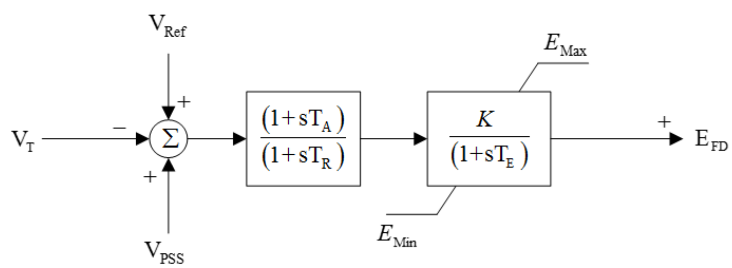


Figure 3-18 The Block Diagram of a Simple Excitation System with PSS.

Fig 3.19 illustrates the block diagram of a simple PSS. speed deviation of generator (i.e. ω) or real power of generator (i.e.P_e) is commonly used input signal .The first block in the figure represents a high pass filter .The purpose of this filter is to stop involvement from a stable state frequency deviation. Second block is known as phase compensation block which is indeed a lead lag form transfer function. The function of this block is to move the phase by setting $T_1$and T_2, so that a positive involvement to damping is achieved.$K_{PSS}$is the stabilizer gain that establishes the magnitude of damping provided by PSS. For the sake of simplicity, the washout block is not considered in this commending. Furthermore, the generator speed deviation (i.e. ω) is used as the input signal.

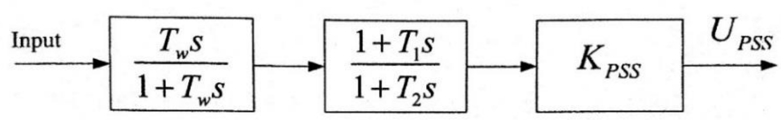


Figure 3-19 Block diagram of simple PSS.

It has already been shown that the dynamic of generator of a represented by the one-axis model is given by

$$\dot{\delta} = \omega$$
$$\dot{\omega} = \frac{1}{M}(P_m - P_e - D\omega) = \frac{1}{M}\left(P_m - \frac{E_q'U}{x_d'}\sin(\delta - \theta) - D\omega\right) \quad (3.39)$$
$$\dot{E}_q' = \frac{1}{T_{d0}'}\left(E_f - \frac{x_d}{x_d'}E_q' + \frac{x_d - x_d'}{x_d'}U\cos(\delta - \theta)\right)$$

Where E_f is constant.

Using the AVR shown in figure 3.16, then E_f is

$$\dot{E}_f' = \frac{1}{T_e}\left(-E_f + K_A\left(U_{ref} + U_{PSS} - U\right)\right) \quad (3.40)$$

If no PSS is utilized then $U_{PSS} = 0$. However, using the PSS shown in figure 3.17 where the washout block is omitted, and the generator speed deviation (i.e.ω) is used as the input signal, then U_{PSS} is a stable variable and its dynamic is given by

$$\dot{U_{PSS}} = \frac{1}{T_2}(-U_{PSS} + K_{PSS\omega} + T_1 K_{PSS\dot{\omega}}) \quad (3.41)$$
$$= \frac{1}{T_2}\left(-U_{PSS} + K_{PSS\omega} + T_1 K_{PSS}\frac{P_m - P_e - D\omega}{M}\right)$$

Thus, the dynamic of a generator and the proposed AVR and PSS models is given by the equation (3.39)-(3.41).

3.8 Curtailment of the Loads from Distribution Grid

In topical years, the electric power distribution network has been undertaking a fundamental shift by an active distribution network (ADN). This pattern shift to ADN is frequently influenced by the promising generation technologies supported on the renewable energy sources (RES) as well as the electrification of the move and heating parts. While enabling chances for big scale saturation of DERs, this conversion also amplifies the insecurity and difficulty in the distribution network operations. For example, dissimilar distribution system operators (DSOs) in Ireland, Italy, Germany and Spain with huge share of fixed RES-based distributed generation (DG) and long feeder lengths understanding voltage limit disobediences in their networks .In the meantime, network completion can be more critical topic in more closely gathered networks like in the Netherlands [18]. Supporting these network resources requires large quantity of investment though the peak loads will normally arise only for small hours in a year [18] .Jamming management techniques in the distribution network can be approximately subdivided into two categories, direct and indirect control approaches [19].The direct approach aspires to moderate the completion by reduction of load and restricted generation. On the other hand indirect approach influences the personal assumes with value and/or incentive based Demand Response (DR) mechanisms. Between the direct approaches, a load shedding plan support on the system eigenvalues and bus modal contribution issue is presented in [20]. A load reduction plan based on power flow tracing is anticipated in ,where the source of over loading and quantity of load to be shed are strong-minded using power tracing simulations on a genuine time base. An under voltage load reduction technique based on Particle Swarm-based Simulated Annealing (PSO-B-SA) optimization is applied in [21] that aims at ensure the voltage steadiness in the distribution network. A GA base load reduction plan is existing in that means to decrease the quantity of shortened load and system losses. An intellectual centralized synchronized algorithm base load shedding approach is presented in [22] allay the network completion while affecting the smallest amount of consumers.

Lately, Universal Smart Energy Framework (USEF) has been introduced as a theoretical approach to raise the elasticity from end-users for different services including overcrowding management in the distribution network [23]. USEF aims to naturally join the indirect and direct approaches of overcrowding management to maximize infrastructure exploitation for the DSO. This enables the DSO to secure litheness from a home capacity market to determine the congestion, whereas the method of elegant deprivation is activated to limit network entrance in terms of connection capacities. This supports the DSO to preserve the network dependability if enough litheness is not available in the network.

CHAPTER 4: SIMULATION AND RESULTS

By using MATLAB programming, the transient stability of SMIB is shown in the block diagram as follows

Block Diagram of Simulation

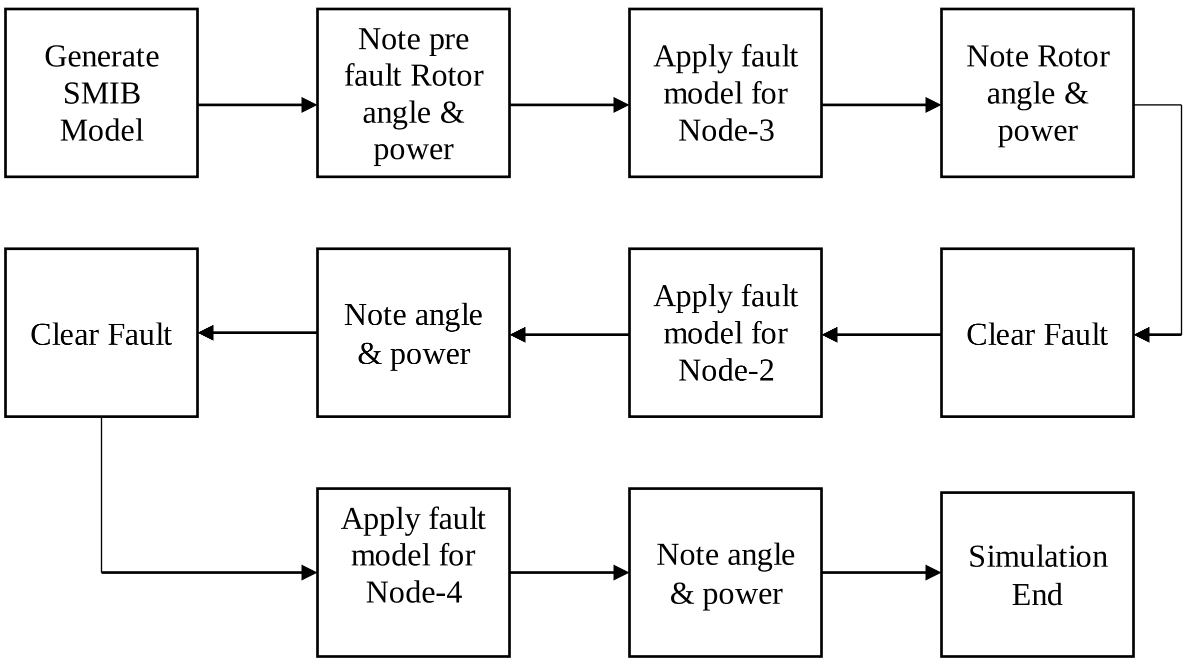


Figure 4-0 Block Diagram of Simultion

The key objective is to investigate and study the transient steadiness of a SMIB System. Transient stability investigation of a power system is anbroad and difficult task. In huge and difficult systems it is often tough to differentiate the basic and important phenomena from the more unrelated one. That's why it is more feasible to analyze a SMIB system to understanding the basic features and use these for a complex network. According to the assignment SMIB system is given below.

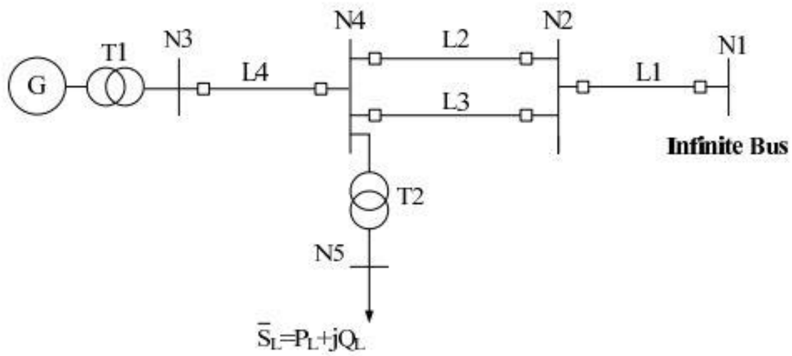


Figure 4-1 Single Machine Infinite Bus (SMIB) system

Transient stability is the capability of power system to preserve synchronism after a huge fault in the system. Mainly it depends on the original operation form of the system. Here classical model is applied for synchronous generator as it has constant emf (E_q') behind the transient reactancex_d'. And the transmission line is lossless.

4.1 Model of the System

In Figure 4-1, a generator G1 is connected to a transmission system at node N3 via a10/130 (kV) step-up transformer T1. Node N1 is considered as an infinite bus. The system supplies a load at node N5 via transformer **T2**. Bus N4 and N2 is connected through parallel transmission line L2 and L3.

According to our assumption, the generator can be modeled by the model of classical, i.e. a constant voltageE_q', after a transient reactance x_d' as shown in Figure 4-2.

Figure 4-2 Generator modeling

According to the assignment we asked to perform our analysis in tow part with fault at two different busses. Let us assume the fault is at bus NX.

We have to calculate every quantity is per unit (PU) and selected base is 130KV and 85MVA. According to the system data magnitude of voltage at bus N3 is 130KV or 1pu.

4.1.1 Thevenin Voltage and Angle

We have to calculate the venin voltage and angle of the SMIB system from node bus N4.

$$\overline{U_{th}} = \frac{Z_l + jx_{t2}}{(Z_l + jx_{t2}) + (jx_{l2} \,||\, jx_{l3}) + jx_{l1}} * U_{n1}\angle 0$$

$$\overline{Z_{th}} = (Z_l + jx_{t2}) \,||(j(x_{l2} \,||\, x_{l3}) + jx_{l1})$$

Where, X_{t2} and $Z_l$is the impedance of Transformer (T2) and load respectively in pu

X_{l1}, X_{l2}, $X_{l3}$is the impedance of transmission line *L1, L2, L3* respectively.

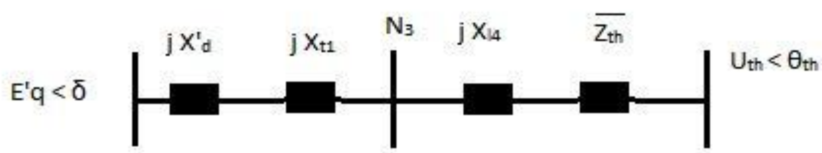


Figure 4-3 Thevenin equivalent circuit

4.2 Node N3 Analysis

Node voltage of bus N3 is given as 130KV or 1pu but it should be calculate the angle of this node. At pre-fault stage mechanical power is equivalent to the electrical power and the equation of $P_e$is

$$P_e = \frac{U_3}{Z^2}\left(U_3 R + U_{th} Z Sin\left(\theta_3 - \tan^{-1}\frac{R}{X} - \theta_{th}\right)\right)$$

Where, $\overline{U_{th}} = U_{th} \angle \theta_{th}$and $\bar{Z} = \overline{Z_{th}} + jX_{l4} = R + j\,X$

From this equation the only unknown variable $\theta_3$can be calculated.

4.2.1 At Pre Fault stage injected Current and Generator bus Voltage (E'_q and δ_0^{pre})

The current injected by the generator $\bar{I}$ and the generator bus voltage $\overline{E'_q}$ can calculate by following equations

$$\overline{I_g} = \frac{\overline{U_3} - \overline{U_{th}}}{j\,(x_{l4} + Z_{th})}$$

$$\overline{E'_q} = U_3 + j(x'_d + x_{t1}) * \overline{I_g} = E'_q \angle\delta_0^{pre}$$

4.2.2 Post Fault Calculation

For simplicity, during fault state will be calculated in later part of the report. To clear the fault at nus *NX*, it should remove L_3. So the venin voltage and impedance will be change along with the electrical power of the system.

4.2.3 Thevenin Voltage and Angle

After removing the faulted line from the system to continue a healthy system with reduced electrical power, the venin voltage and angle may be calculated as

$$\overline{U_{th}} = \frac{Z_l + jx_{t2}}{(Z_l + jx_{t2}) + jx_{l2} + jx_{l1}} * U_{n1}\angle 0$$

$$\overline{Z_{th}} = (Z_l + jx_{t2})\,||(jx_{l1} + jx_{l2})$$

4.2.4 At Pre Fault stage injected Current and Generator bus Voltage (E'_q and δ_0^{post})

Here we using the classical modeling of generator to the magnitude of E'_q will same at post fault stage. After thevenin equivalent it can be found a very simple circuit. Where total impedance is *Z*

$$\bar{Z} = jx_{G1} + jx_{T1} + jx_{l4} + Z_{th}$$

$$P_m = P_e^{post} = \frac{E'_q}{Z^2}\left(E'_q R + U_{th} Z Sin\left(\delta_0^{post} - \tan^{-1}\frac{R}{X} - \theta_{th}\right)\right)$$

Where, $\overline{U_{th}} = U_{th} \angle \theta_{th}$ and $\bar{Z} = R + j\,X$

From this equation the only unknown variable δ_0^{post} can be calculated.

4.3 During Fault Calculation

According to the place of faulted bus the equivalent model will be different, so the critical clearing angle and time will be vary. If it observed carefully to the trajectory of the SMIB system, for transiently stable system ω should be zero. So the rotor angle is maximum when it comes back at oscillation.

$$\omega = 0 \quad or \quad \dot{\delta} = \omega = \frac{d\delta}{dt} = 0$$

In this stage we have to calculate the maximum rotor angle for a stable system using equal area criterion.

4.3.1 When NX=N4

If it occurs any fault at bus N4 then we can find the equivalent circuit like figure 4-4. The transmission line is lossless so that the electrical power at the time of fault is zero during the fault condition.

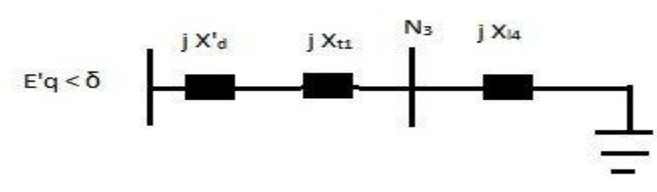


Figure 4-4 Fault at bus N4

Using equal area criteria we have to compute the accelerating region and the decelerating region to find δ_{cc}. Here P_e during fault is zero. So

Accelerating area, $A_a = \int_{\delta_{s}pre}^{\delta_{cc}} \left(P_m - P_e^f\right) d\delta$

Decelerating area, $A_d = \int_{\delta_{cc}}^{\delta_{max}} \left(P_e^{post} - P_m\right) d\delta$

Solving $A_a = A_d$ we can find a equation,

$$K_1\delta_{cc} + (-K_2)\cos(\delta_{cc} - K_3) - (\,P_m\big(\delta_s^{pre} - \delta_{max}\big) + K_1\delta_{max} - K_2\cos(\delta_{max} - K_3)) = 0$$

Where $\delta_{max} = 180 - \delta_s^{post} + 2 * K_3^{post}$, $K_1 = \left(\frac{E'q}{Z}\right)^2 * R$,$K_2 = \left(\frac{E'q*U_{th}}{Z}\right)$, $K_3 = \tan^{-1}\frac{R}{X} + \theta_{th}$

Solving the equation we can findδ_{cc}. Further we have to calculate critical clearing angle (t_{cc}) following the equation as follows

$$t_{cc} = \sqrt{\frac{2M}{P_m}\,(\delta_{cc} - \delta_s^{pre})} \qquad (4.1)$$

4.3.2 When NX=N2

Now for analysis fault at bus N2, for the connected load at N4 electrical power is now zero.

$$P_e^f = Real\big[\overline{E_q}' * \overline{I_f^*}\big] and \overline{I_f} = \frac{\overline{E_q'}}{\overline{Z_{tot}}}$$

Here, Ztotal=XG1+XT1+XL4+parallel(parallel(XL2,XL3),Zload+XT2)

Now for δ_{cc} and t_{cc}it should solve the equal area criteria according to section 4.3.1

$$t_{cc} = \sqrt{\frac{2M}{P_m - P_e^f}\,(\delta_{cc} - \delta_s^{pre})} \qquad (4.2)$$

4.3.3 Simulation and Results

MATLAB® simulation code is provided results.

4.3.4 Fault at NX=N4

After simulation at MATLAB using Bnumber =13 we can determine δ_{cc} and t_{cc} as follows-

$$E_q' = 1.0687pu$$

$$\delta_0^{pre} = 23.6619(\text{deg})$$

$$\delta_0^{post} = 27.0042\ (\text{deg})$$

$$\delta_{cc} = 65.1881\ (\text{deg})$$

$$t_{cc} = 0.2615\ (\text{sec})$$

Now at MATLAB we can plot the Rotor angle vs pre, post and during fault electrical power in (Figure 4-5)

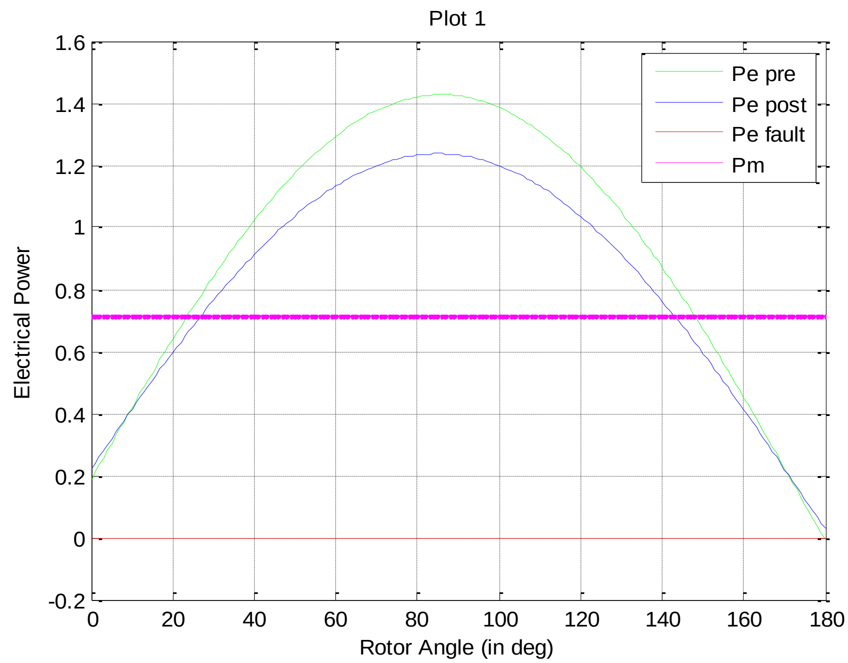


Figure 4-5 Rotor angle vs Power (Plot 2)

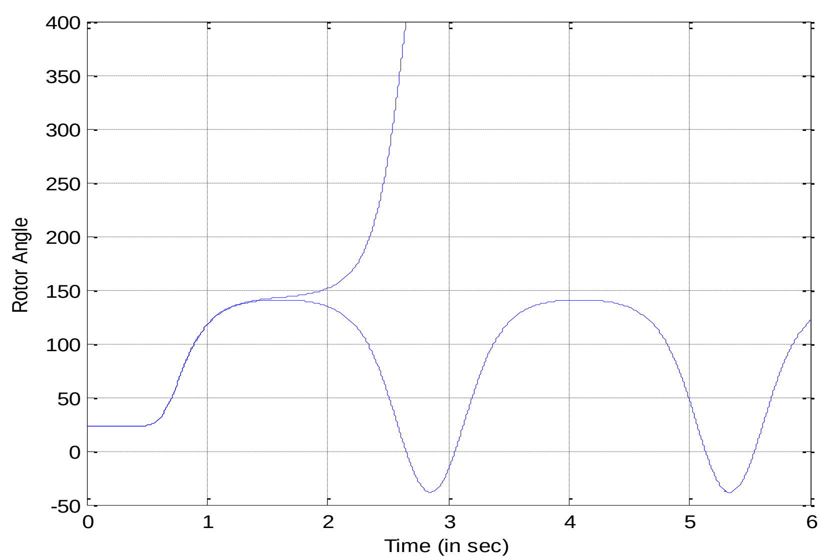


Figure 4-6 Time vs Rotor angle

At Figure 4-5 is can be find that at $\delta_0^{pre} = 23.6619$ (deg)the prefault electrical power and mechanical power is equal. After a large fault at N4, rotor angle will start oscillation. Now we have to analyze Figure 4-6 for to different time tc1=tf+tcc+0.0001,tc2=tf+tcc-0.0001. It is very clear that for a very little delay after the critical clearing time, the system will drop synchronism and will be unstable because frequency will reduce.

Now for further investigation just increase the simulation period up to 20sec. Here damping is zero so the rotor angle will oscillate within a certain limit in Figure 4-7.

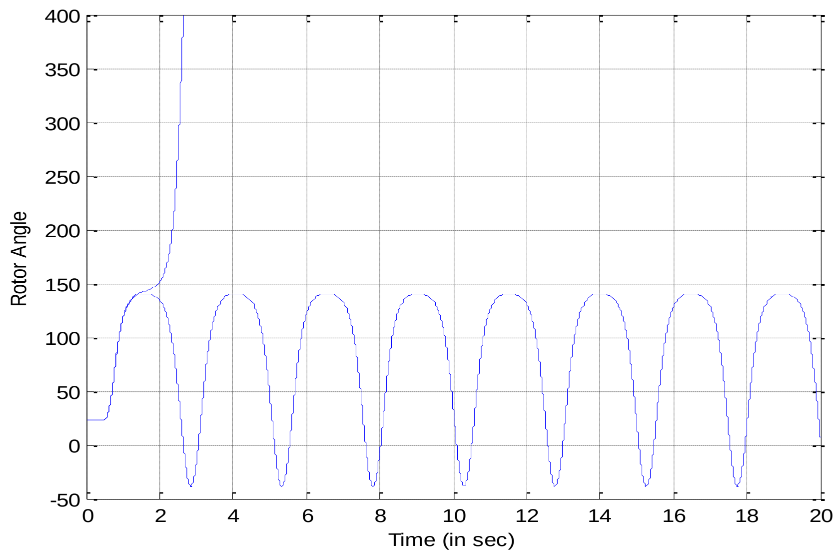


Figure 4-7 Time vs Rotor angle

Now for further investigation just increase the simulation period up to 40sec. Here damping is zero so the rotor angle will oscillate within a certain limit in Figure 4-8.

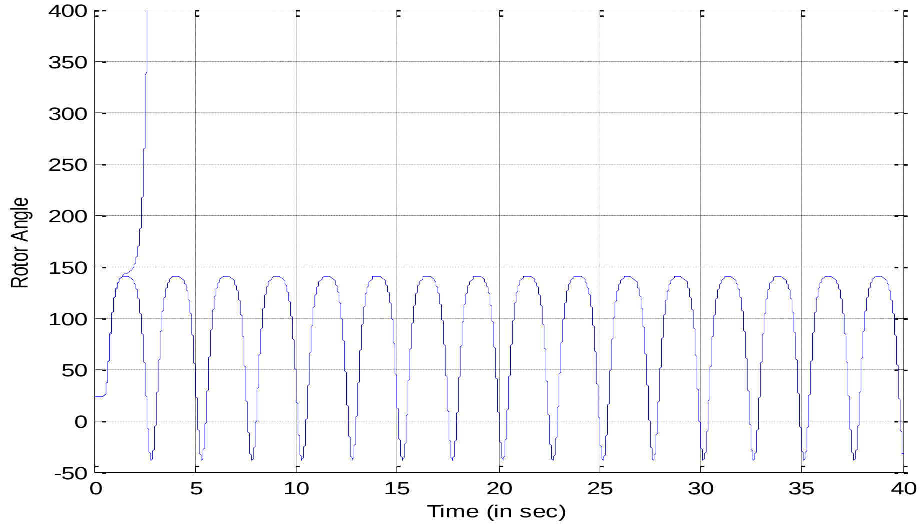


Figure 4-8 Time vs Rotor angle

4.3.5 Fault at NX=N2

Obtained result from simulation is given below,

$$E_q' = 1.0687\ pu$$

$$\delta_0^{pre} = 23.6619\ (\text{deg})$$

$$\delta_0^{post} = 27.0042\ (\text{deg})$$

$$\delta_{cc} = 66.2984\ (\text{deg})$$

$$t_{cc} = 0.2708\ (\text{sec})$$

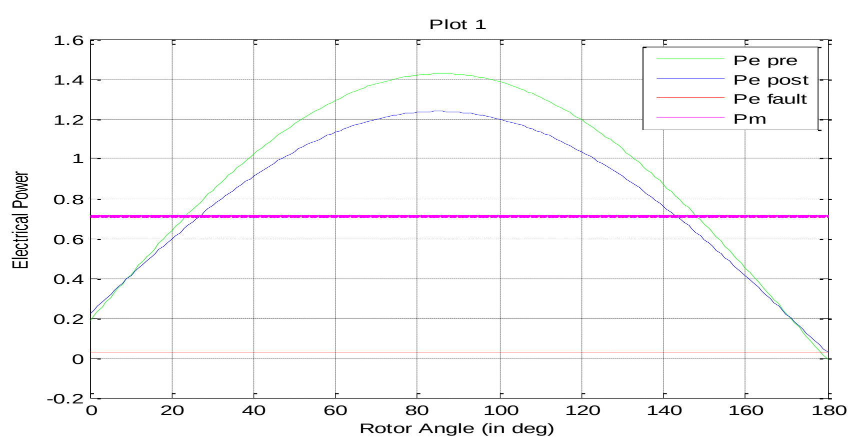


Figure 4-9 Rotor angle vs Power (Plot 1)

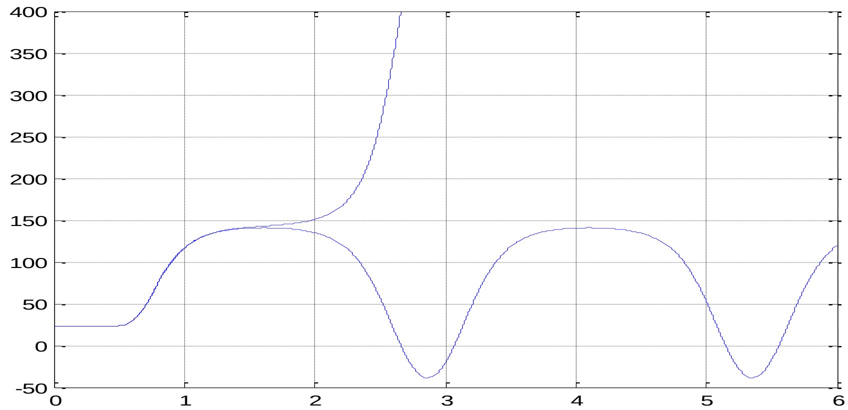


Figure 4-10 Time vs Rotor angle

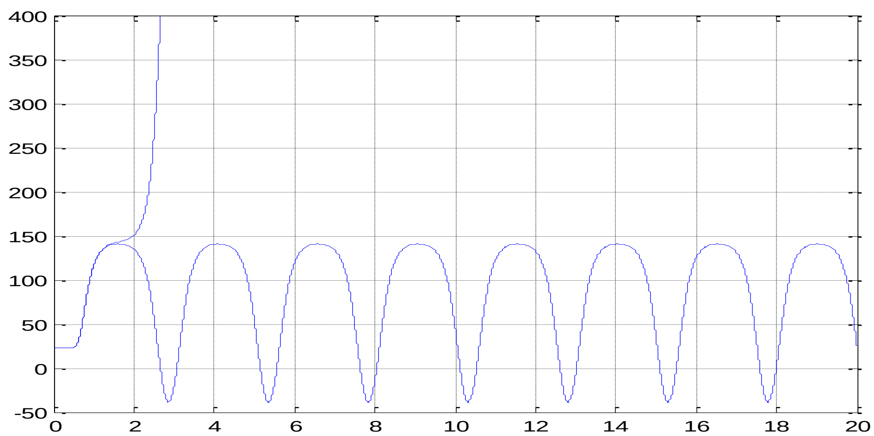


Figure 4-11 Time vs Rotor angle

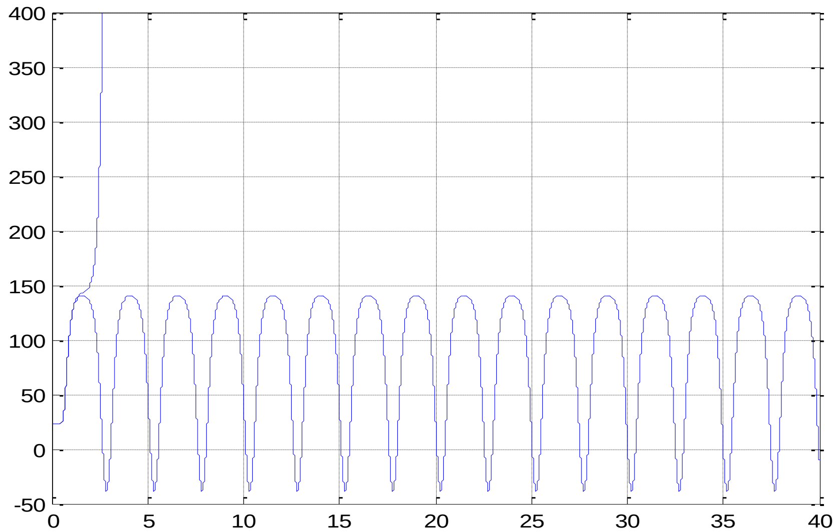


Figure 4-12 Time vs Rotor angle

Same characteristics of the system can be found in Figure 4-11 but now for the load the Electrical power is not zero. Now from equation (4.1) and (4.2) it is very clear that for P_e^f the critical clearing time will be a little higher for NX=N2 rather than N4. Even for this non zero electrical power for fault at bus N2 critical clearing angle is higher for NX=N2 because of position of the buses. Node bus N4 is nearer than node bus N2. Analytically it can be stated that, when P_e^f not zero then accelerating area will be less than that of decelerating area. So to increase A_1 it should move the rotor angle to the left to make $A_1 = A_2$ and the δ_{cc} will increase along with t_{cc}.

4.3.6 Chapter Summary

Transient stability of a SMIB system is very important to realize the synopsis of a complex network, though modern electrical network is the complex man made network in world. During steady state, mechanical power through the prime mover is equal to the electrical power delivers by the generator. Meanwhile when the system is experienced some sort of large fault (as shown above), the P_m and P_e become imbalance and the generator stars accelerating or decelerating. If the fault is large enough then it should disconnect the generator form the system, but it should avoid. So we have to calculate the maximum allowable time or critical clearing angle to comprehensible the fault to maintain the stability of the system.

In our study we saw that if the system is Single Infinite bus system and the number of generator in the system is not more than one then the fault ensue in the area which is close to the generator is more vulnerable than the area which is away from the generator, fault area which is close to the generator can make the system completely unstable and there is a possibility of permanent damage.In our study we have chosen busN_4 and N_2 as fault location.Bus N_4which is closer to generator than N_2, fault at $N_4$is found to be dangerous than fault at N_2.

In this result and simulation part we saw that after a large fault at N_4bus the system becomes unstable because of the electrical power output which is zero but fault atN_2 bus the system remain stable and oscillatory too which indicates that the resultant of the wave shape is always zero and the wave will go on and go an.

To make a system stable which is not stable in any condition earlier we discussed we used some other systems which remove the system instability four system is being used first one was an excitation system with rotating exciters which is generally performed by voltage regulator,second one was another excitation system but static,third one was excitation system with power system stabilizer and the last one was one axis model which includes AVR and power system stabilizer with a constant $E_f$apart from that we also used simple excitation system to make the system stable.

In this part we saw the change of graph after fault and before fault which is denoted by pre-fault and post-fault in the wave shape which was drawn by the value of rotor angle and power denoted as rotor angle vs power graph shows that when the fault take place the load increase and the power reduces.

From our study we utilize or like to propose that solution from the generation side can be avoid by using solution from the distribution side .Solution from the generation side is always complex and expensive as per the equipment complexibility and cost concern and it also results in a high power loss.There are few methods of solution from the distribution side if we follow the curtailment process three curtailment techniques can be done in this three curtailment techniques soft curtailment is better because the curtailment can be done by calculating or indicating the essential loads in the distribution side by this techniques we don’t need to curtail all the load.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATION

5.1 Conclusion

This thesis paper is about the steadiness of power system. There are several types of steadiness which have included for the analysis. However, this thesis paper is mainly focused on Rotor angle steadiness. The papers are demonstrated the different types of stability like as transient stability, small signal stability and the dynamic stability. Related with rotor angle of any machine The stability of power system can be unstable due to sudden load changing, generation loss.

For the purpose of analysis different types of stability there have to consider few fundamental mathematical modeling. By different basic modeling solve differently the fault of power system and make the system stable after being fault in the system. The models are working with an initial condition which is known as pre-fault condition. On the basis of pre-fault condition the system is making stable from an unstable or faulty state. There have to consider basic parameters to make the operation of making the system stable from an unstable state that are swing equation ,power angle curve , equal area criterion, transfer reactance.

On the methodology portion of this thesis paper mainly focused on the theory demonstration of few basic model for stability of the power system. Firstly focused on the SMIB network. For a SMIB network the classical model is better to analysis system stability. For classical model there have to work on the steadiness of the equilibrium points of the SMIB system. For this operation of the equilibrium points of the SMIB system some theorem have to demonstrate like as Lyaponov's direct and indirect method which is describe in the appendix portion .The fault is solved by controlling the load from the distribution side of the system. A proper load modeling is essential for planning the curtailment loads. The load modeling can be a static or dynamic load model. Although dynamic load modeling is more and more precise than the static load modeling but static load modeling is usually used for transient stability. For multi-machine bus system there have few models which has been analyzed in the result section.

In the control of stability there is added an additional excitation system with the one axis model. The excitation system of generator consists of an automatic voltage regulator (AVR) and an exciter. The primary operation of an exciter is to supply a dc source for field excitation of a synchronous generator and the AVR controls.

Regarding steadiness of the power system, the following conclusion are drawn from the result and the simulation portion of this paper,

1. First step of analysis of the stability or solving the fault is to model the whole system. In this paper the system is modeled for classical model and make the assumption according to the classical model. Also consider fault two different buses and calculate the every quantity is per unit(PU).
2. Fault can be occur at any bus of the network. If the fault occur at the nearest bus of the generation side of the system is much more vulnerable. It is always difficult to make the system stable again if the fault is occur at the nearest bus of the generation side of the network.

3. Load curtailment is the most feasible and easier way to regain the stability of the system after being faulted.
   Load curtailment the curtailing of the active power from the system after being faulted. The curtailment is not done randomly. How much amount of load need to be curtail is decided based on fault?

4. Load curtailment have to be made smartly and curtail the active power at an optimum level. The curtailment can be made by various ways and the curtailment is done based on the firm and non-firm capacity. Few possible ways are following ,

   - In the Feeder non-firm capacity is selection based.
   - In the Feeder power flow is selection based.
   - Fair Power reduction.
   - Security Constrained Optimal Power Flow (OPF).

Simulation results of Node N4 and Node N2:

For Node N4

Critical Clearing Angle = 65.1881 (deg) and Critical Clearing Time = 0.2371 (sec)

For Node N2

Critical Clearing Angle = 66.2984 (deg) and Critical Clearing Time = 0.2708 (sec).

5.2 Recommendation

Future developments for load curtailment based system stability is shown as follows. Complete and detailed analysis of these points are explained in Appendix- .

A. Firm and non-firm capacity

i. Firm capacity – conventional contract that defines the amount of power that must be supplied at all time
ii. Non-firm capacity – extra contract that defines the amount of power curtailed on emergency situation only

B. **Minimization of the curtailment cost** – optimum plan for curtailment to minimize curtailment cost based on contract type or selection rules.

C. **Greedy selection rules** – optimized selection of curtailment option based on rules as in

i. Selection based on Non-firm capacity of the feeder
ii. Selection based on power flow in the feeder

Appendix

Appendix-1

Lyapunov's Direct Method: The equilibrium point $\mathrm{x_0}$ of $\frac{\mathrm{d}}{\mathrm{dt}}\mathrm{x(t)} = \dot{\mathrm{x}} = \mathrm{f(x)}$ is stable if a continuously differentiable scalar function $\mathcal{V}(\mathrm{x})$ can be found fulfilling the following conditions:

i. $\mathcal{V}(x_0) = 0$

ii. $\mathcal{V}(x) > 0$ *for all* $x \in D$, *except at* x_0

iii. $\dot{\mathcal{V}}(x) = \frac{\partial \mathcal{V}(x)}{\partial x}.\, f(x) \leq 0$ *for all* $x \in D$

The equilibrium point $\mathrm{x_0}$ is asymptotically stable if conditions i.-ii. hold, and

iv. $\dot{\mathcal{V}}(x) < 0$ *for allx* $\in D$, *except at* x_0 *where* $\dot{\mathcal{V}}(x_0') = 0$

Or, alternatively

v. $\dot{\mathcal{V}}(x) \leq 0$,*Provided that* $\dot{\mathcal{V}}(x)$ *is not identically zero on any solution x(t) in D, except at* x_0.

A function $\mathcal{V}(x)$ satisfying the above conditions is called Lyapunov function.

Stability of the equilibrium point of $\frac{d}{dt}x(t) = \dot{x} = f(x)$ can be distinct by investigative the linearized system. This approach is known as Lyapunov's indirect method. Linearizing the nonlinear system $\frac{d}{dt}x(t) = \dot{x} = f(x)$ around the equilibrium pointx_0, we obtain

$$\Delta\dot{x} = A\Delta x$$

Where
$$A = \left[\frac{\partial f(x)}{\partial x}\right]_{x=x_0} = \begin{bmatrix} \frac{\partial f_1(x)}{\partial x_1} & \cdots & \frac{\partial f_1(x)}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n(x)}{\partial x_1} & \cdots & \frac{\partial f_n(x)}{\partial x_n} \end{bmatrix}_{x=x_0}$$

Which is also called the Jacobain matrix at x_0. The eigenvalues of A (i.e.) are obtained by solving

$$|A - \lambda \underline{1}| = 0$$

Where $\underline{1}$ is an identity matrix.

APPENDIX-2

Let x_0 be the equilibrium point of the non-linear system $\frac{d}{dt}x(t) = \dot{x} = f(x)$. Then,

- x_0 is asymptotically steady if all the eigenvalues of the matrix A having negative real parts.
- x_0 is unstable if any of the eigenvalues has a positive real part.

Note that Appendix-2 generally not applicable if some of the eigenvalues have zero real parts and the others have negative real parts. Thus, we can draw finish about the local steadiness or instability of the linearized method $\Delta\dot{x} = A\Delta x$, provided none of the eigenvalues of the linearized system have zero real parts.

Future Development

Steadiness of Transmission Grid Using Load Curtailment

A distinctive LV network is planned and worked radially without any idleness. So, any occurrence happening at theMV/LV transformer, e.g. overcrowding when transformer loading *S total* beats the rated capacity S_{max}, will influence all the end users down-stream of the transformer. To manage with such growing events, USEF explains a procedure so that the DSO can limit the network entrée for confident number of connected end users to improve the load of the transformer inorder to reduce the blocking. It can be done by shortening active power utilization at the connecting points by total reduced power that can be exposed as follows:

$$S_{curtailed} \geq |S_{total}| - |S_{max}| \qquad (5.1)$$

A. Firm and Non-Firm Capacity

At this paper, a bendable capacity agreement is introduced todecide the short enable power of the end users with different levels of consistency for different kinds of connections. This may be understood by means of firm and non-firm capacities, defined by the following:

The overall capacity at any connecting point *I* canbe explained as the addition of the contracted firm and nonfarm capacities as follows:

$$P_i = P_i^{firm} + P_i^{nonfirm} \qquad (5.2)$$

B. Minimizing the Curtailment Cost

Optimum plan for curtailment to minimize curtailment cost based on contract type or selection rules. Theoptimization trouble can be accurately expressed as:

$$\min_{i\epsilon NF, j\epsilon NB_i} \sum_{i=1}^{NF} \left(u_i . C_i + \sum_{j=1}^{NB_i} P_{ij,curtail} . C_{ij} \right) \qquad (5.3)$$

Subject to,

$$u_i = \begin{cases} 1 \; iffeederiisselected \\ 0 \quad otherwise \end{cases} \qquad (5.4)$$

$$\sum_{j=1}^{NB_i} P_{ij,curtail} \geq |S_{curtailed}| \qquad (5.5)$$

$$0 \leq P_{ij,curtail} \leq u_i . P_{ij,nonfirm} \qquad (5.6)$$

Equation. (5.6)-(5.8) describe the restraint of the optimizationtrouble. Constriction in eq. (5.7) is forced to limit the reduction to keep the loading of the transformer close to the supposed rated value, while equation. (5.8) confirm that only the nonfarm capacity of the chosen feeder is considered for thereduction in equivalent buses.The optimization trouble expressed in equation (5.5)-(5.8) consists of both binary and integralvariables and can be answered by Mixed Integer Programming (MIP) method.

C. Greedy Selection Rules

Greedy Selection Rules are expressed as follow:

1) Selection Based on Non-Firm Capacity in the Feeder

The intend of the process is to slot in the lowest number of feeders to solve the jamming. When a feeder is selected, all the buses in the preferred feeder will be considered for reduction.

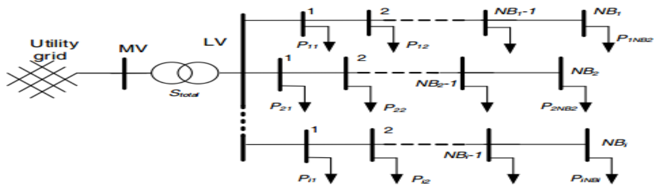


Figure App.2- Radial Topology of LV Distribution Network

In fact, the optimization trouble is a facilitate form of equation (5.5) and can be reformulated as follows:

$$\min_{j\epsilon NB_i} \sum_{j=1}^{NF}\left(\sum_{j=1}^{NB_i} P_{ij,curtail}.\, C_{ij}\right) \qquad (5.7)$$

$$\sum_{j=1}^{NB_i} P_{ij,curtail} \geq |S_{curtailed}| \qquad (5.8)$$

$$0 \leq P_{ij,curtail} \leq P_{ij,nonfirm} \qquad (5.9)$$

As shown in equation. (5.10) and (5.11) the restraint limit the quantity of reduction in the buses inside the presented non-firm capacity whereas the entire reduction in the network must be sufficient to solve the overcrowding.

2) Selection Based on Power Flow in the Feeder

The feeders can be selected for reduction by position based on the flows exposed by a preliminary load-flowcomputation. The feeders have maximum load contribute more to the overcrowding and reducing active power in the feeder can determine the overcrowding powerfully. Once the feeders are selected the trouble can be solved by using the similar method as explained in step 2 and 3 for the selection of feeders based on the presented non-firm capacity following equation. (5.9) - (5.11).

ABBREVIATIONS

AVR – Automatic Voltage Regulator

TSM – Transient Stability Margin

SMIB – Single Machine Infinite Bus

EAC – Equal Area Criterion

SPM – Structure Preserving Model

RNM – Reduced Network Model

KCL – Kirchhoff's Current Law

TEF – Transient Energy Function

SIME – Single Machine Equivalent Method

DC – Direct Current

AC – Alternating Current

PSS – Power System Stability

AND – Active Distribution Network

RES – Renewable Energy Sources

DSO – Distribution System Operator

DG – Distributed Generation

DR – Demand Response

PSO-B-SA – Particle Swarm-based Simulated Annealing

USEF – Universal Smart Energy Framework

MIP – Mixed Integer Programming

MV – Medium Voltage

LV – Low Voltage

PU – Per Unit

OPF – Optimal Power Flow

SG – Single Generator

Description of the Terms

E’(q) = constant emf of synchronous generator

X’(d) = transient reactance

P(m) = mechanical power

P(e) = electrical power

T(e) = electromagnetic torque

T(s) = shaft or load torque

T(a) = net accelerating torque

P(s) = shaft power

P(a) = rotoe accelerating power

E(f) = no load excitation voltage

V(t) = generator terminal voltage

X(s) = synchronous impedance

M = angular momentum of generator motor

ω = angular speed between the rotor axis and stator field axis

δ = generator rotor angle

δ(c) = clearing angle

δ(cc) = critical clearing angle

t(c) = clearing time

t(cc) = critical clearing time

U(L) = actual bus voltage magnitude

U(L0) = initial value of the voltage

P(LO) = active power at U(LO)

Q(LO) = reactive power at U(LO)

D(pk) and D(qk) = damping constants

Z(l) = impedance of the load

X(t1, t2, t3,....) = impedance of the transformer T1, T2, T3,....respectively

X(l1, l2, l3,......) = impedance of the transmission line L1, L2, L3,.....respectively

Jx(tot) = sum of the reactance of the transmission line and the two transformers

N1, N2, N3, N4,.........= bus

NX = fault is at bus N1, N2, N3,.....etc

REFERENCES

[1] B. Pal, B. Chaudhuri and V.-0.-3.-2.-5. Book of Robust Control in Power Systems pages 460, Power Electronics and Power Systems, 2005.

[2] A. Jha, L. Ralte, A. Kumar and P. R. Pati, "TRANSIENT STABILITY ANALYSIS USING EQUAL AREA CRITERION," 2008-09.

[3] H. Saadat, Power System Analysis, WCB McGraw-Hill, 1999.

[4] J. S. Patel and M. N. Sinha, "Power System Transient," in *IEEE National Conference on Recent*, V.V.Nagar,Gujarat,India, 2011.

[5] J.Tamura and T. a. I.Takeda, New Approach For Steady State, IEEE Transaction on Energy, 2011.

[6] A. Liamas and J. D. L. Ree, "Stability and The transient".

[7] Y.Dong and H.R.Pota, *Transient Stability Margin Prediction Using Equal*, 2011.

[8] T. Miki, D. Okitsu, E. Takashima, Y. Abe and M. Tano, "Power Transient Stability Assesment By Using Critical Fault," 2002.

[9] A. N.Michel, A.A.Fouad and V. Vittal, "Power System Transient," 2009.

[10] J. Tamura, M. Kubo and T. Nagano, "A Method Of Transient," *Stability Simulation of Unbalanced Power System.*

[11] M. A. Pai, Energy Function Analysis for power System Stability, Kluwer Academic Publishers, 1989.

[12] I. T. F. o. L. R. f. D. performance, "Load Representation for Dynamic Performance Analysis," vol. 8, no. 2, May 1993.

[13] "Standard Load Models for Power Flow and Dynamic Performance Simulation," *IEEE Task Force on Load Representation for Dynamic performance*, vol. 10, no. 3, August 1995.

[14] I. T. F. o. l. r. f. D. performance and L. r. f. D. p. Analysis, "IEEE Transactions on Power Systems," vol. 10, no. 1, February 1995.

[15] M. Pavella, D. Ernst and D. Ruiz-Vega, Power System Transient Stability Analysisand

Control, Kluwer Academic Publishers, 2000.

[16] D. Ruiz-Vega and M. Pavella, "Comprehensive Approach to Transient Stability and Control: (PART I and PART II)," vol. 18, Nov. 2003.

[17] P. Kundur, Power System Stability and Control, McGraw-Hil] Inc, 1994.

[18] R. A. Verzijlbergh, L. J. D. Vries and Z. Lukszo, "Renewable Energy Sources and Responsive Demand. Do We Need Congestion Management in the Distribution Grid?," vol. 29, p. 2119–2128, 2014.

[19] S. Huang, Q. Wu, Z. Liu and A. H. Nielsen, "Review of congestion management methods for distribution networks with high penetration of distributed energy resources," pp. 1-6, 2014.

[20] A. Arief, M. B. Nappu, Z. Y. Dong and M. Arief, "Load curtailment strategy in distribution network with dispersed generations," pp. 1-6.

[21] N. Sadati, T. Amraee and A. M. Ranjbar, "A global Particle Swarm Based-Simulated Annealing Optimization technique for under-voltage load shedding problem," vol. 09, p. 652–657, 2009.

[22] D. Panasetsky, N. Tomin, D. Yang and V. Kurbatsky, "A New Intelligent Algorithm for Load Shedding Against Overload in Active Distribution Networks," in Power System Technology (POWERCON);2014 International Conference, 2014.

[23] "An introduction to the Universal Smart Energy Framework," USEF Summary; 2014.