BEFOREHAND OBTAINING A SAFETY OPERATION CONDITION BY USING DAILY LOAD CURVES IN TRANSIENT STABILITY AND GRAPHICAL SOFTWARE FOR TRANSIENT STABILIY APPLICATIONS

CELAL ÖZTOP

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Approval of the Graduate School of (Name of the Graduate School)

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ABSTRACT

BEFOREHAND OBTAINING A SAFETY OPERATION CONDITION BY USING DAILY LOAD CURVES IN TRANSIENT STABILITY AND GRAPHICAL SOFTWARE FOR TRANSIENT STABILIY APPLICATIONS

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In this thesis, relationship between two most important transient stability indices, critical clearing time and generator rotor angle is examined for one machine-infinite bus system and then extended to the multimachine case and is observed to be linear.

By using the linear relationship between critical clearing time and generator rotor angle and utilizing the daily load curve, a new preventive method is proposed. The aim of this method is to make all critical clearing times longer than the relay and circuit breaker combination operation time. In the proposed method, desired critical clearing times are obtained by using on line system data and daily load curves. Then desired values are adjusted by generators output rescheduling and terminals voltage control

Visual computer language is used for graphical and numerical solutions. Comprehension of one machine infinite bus system and multimachine system transient stability become easier.

Keywords: Critical clearing time, power system transient stability

ÖZ

GÜNLÜK YÜK EĞRİLERİNİ KULLANARAK GEÇİCİ HAL KARARLILIĞI İÇİN ÖNCEDEN GÜVENLİ ÇALIŞMA DURUMUNUN ELDE EDİLMESİ VE GEÇİCİ KARARLILIK UYGULAMALARI İÇİN BİLGİSAYAR PROGRAMI

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Danışmanr: Prof. Dr. Arif Ertaş

Ağustos 2005, 73 sayfa

Bu tezde, geçici hal karalılığın iki en önemli indisi, kritik temizleme zamanı ve jeneratör rotor açısı arasındaki ilişki tek makine sonsuz bara sisteminde daha sonra çok makineli sistemde incelenmiş ve lineer olduğu görülmüştür.

Kritik açma zamanı ve jeneratör rotor açısı arasındaki lineer ilişkiyi kullanarak ve günlük yük eğrilerinden faydalanılarak geçici hal kararlılık için yeni bir önleyici metot öne sürülmektedir. Bu metodun amacı bütün kritik açma zamanlarını kesici ve röle çalışma zamanından daha büyük yapmaktır. Öne sürülen metotta istenilen kritik açma zamanları on-line sistemden ve günlük yük eğrilerini kullanarak elde edilmiştir. Daha sonra bu değerler jeneratörlerin çıkış güçlerini ve terminal voltajlarını yeniden düzenleyerek ayarlanmıştır.

Grafikler ve nümerik çözümler için görsel bilgisayar programlama dili kullanılmıştır. Böylece tek makine sonsuz bara sistemi ve çok makineli sistemin incelenmesi daha kolay olmuştur.

Anahtar Kelimeler : Kritik açma zamanı, güç sistemleri geçici hal kararlılığı

ACKNOWLEDGMENTS

The author wishes to express his deepest gratitude to his supervisor Prof. Dr. Arif Ertaş for their guidance, advice, criticism, encouragements and insight throughout the research.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

Today, energy consumption is increasing continuously due to growing of the world and technological developments. In order to provide this consumption a large power system with hundreds of machines and its interconnections must be designed and operated correctly. At this point, stability of power system becomes more important. In this work, by utilizing the daily load curves a new preventive control method is proposed in order to achieve a more stable operating point for power systems.

To carry out preventive control method, first transient stability studies must be done. These studies provide the information related to the capability of a power system to remain in synchronism in major disturbances resulting from either the loss of generating or transmission facilities, sudden or sustained load changes or momentary faults. Specifically these studies provide the changes in voltages, currents, powers, and torques of the machines of the power system during and immediately following a disturbance. All these are used in designing the power system to be stable under any probable disturbance

Power system design becomes increasingly difficult in present days because of large, heavily interconnected systems with hundreds of machines. These machines and interconnected system are modeled in order to reflect the correct dynamic performance of the system. The synchronous machines are represented by simplified model. Loads are represented by a static admittance to ground and network is represented by algebraic equations. The bus admittance matrix used in network equation must be modified to reflect the changes in the representation of the network.

A transient stability analysis is performed by combining a solution of the algebraic equations describing the network with a numerical solution of the differential equations. As a result rotor angles and critical clearing times are determined from transient stability studies.

In chapter three, a new preventive control method is introduced. This method deals with the relationship between the rotor angles and the critical clearing times. The aim of this method is to determine the contingencies beforehand by using the relationship and then, prevent them by applying a control method. The relationship is first studied on a single machine infinite bus system which is consist of generator, transmission lines and infinite bus. Three phase to ground faults, these are severest ones, are considered at the different regions of the system. The relationship is determined by utilizing the equal area criterion. The results are encouraging in order to extend the study on multimachine case.

In multimachine case, a simulation study on IEE of Japan EAST 10 machine system is used. The simulation is performed at different load condition by taking into consideration of severest faults. Again the relationship between critical clearing times and generator rotor angles are determined. By using these results and daily load curves a new preventive control method is proposed.

The necessity of this method is determined by comparing critical clearing times which are obtained for future condition and predefined values (the actual operating times of the circuit breaker and relay combination). If necessary then preventive control method is applied by using generator output rescheduling and terminal voltage control.

By the means of this method whole power system and all contingencies can be observed and more stable operating point is achieved.

CHAPTER 2

TRANSIENT STABILITY STUDIES

2.1 Introduction

Transient stability studies provide information related to the capability of a power system to remain in synchronism during major disturbances resulting from either the loss of generating or transmission facilities, sudden or sustained load changes, or momentary faults. Specifically, these studies provide the changes in voltages, current, powers, speeds, and torques of the machines of the power system, as well as the changes in system voltages and power flows, during and immediately following a disturbance. The stability of power system is an important factor in planning of new facilities. In order to provide the reliability required by the dependence on continuous electric service, it is necessary that power systems be designed to be stable under any conceivable disturbance.

Power system design becomes increasingly difficult in present day because of vast, heavily interconnected systems with hundreds of machines. These machines and interconnected system are modeled in order to reflect the correct dynamic performance of the system. The resultant equations describing the network and machines are solved in transient stability studies with numerical methods.

This chapter describes modeling considerations, solution methods applicable to transient stability analysis.

2.2 Rotor Dynamics and The Swing Equation

The equation governing rotor motion of a synchronous machine is based on the elementary principle in dynamics which states that accelerating torque is the product of the moment of inertia of the rotor times its angular acceleration, i.e., [1]

$$J\frac{d^2\theta_m}{dt^2} = T_a = T_m - T_e \qquad \text{N-m} \tag{2.1}$$

where,

J : the total moment of inertia of the rotor masses, in kg-m^2

θ_m : the angular displacement of the rotor with respect to a stationary axis, in mechanical radians (rad)

t : time, in seconds(s)

T_m : the mechanical or shaft torque supplied by the prime mover less retarding torque due to rotational losses, in N-m

T_e : the net electrical or electromagnetic torque, in N-m

T_a : the net accelerating torque, in N-m

Since θ_m is measured with respect to a stationary reference axis on the stator, it is an absolute measure of rotor angle. Consequently, it continuously increases with time even at constant synchronous speed. Since the rotor speed relative to synchronous speed is of interest, it is more convenient to measure the rotor angular position with respect to a reference axis which rotates at synchronous speed. Therefore, it is defined

$$\theta_m = \omega_{sm}t + \delta_m \tag{2.2}$$

where ω_{sm} is the synchronous speed of the machine in mechanical radians per second and δ_m is the angular displacement of the rotor, in mechanical radians, from the synchronously rotating reference axis. The derivative of equation 2.2 with respect to time is

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

$$\frac{d^2\theta_m}{dt^2} = \frac{d^2\delta_m}{dt^2} \tag{2.3}$$

Substituting equation 2.3 in equation 2.1, it is obtained

$$J\frac{d^2\delta_m}{dt^2} = T_a = T_m - T_e \qquad \text{N-m} \tag{2.4}$$

We recall from elementary dynamics that power equals torque times angular velocity, and so multiplying equation 2.4 by ω_m, we obtain

$$J\omega_m \frac{d^2\delta_m}{dt^2} = P_a = P_m - P_e \qquad \text{W} \tag{2.5}$$

where

P_m : shaft power input to the machine less rotational losses

P_e : electrical power crossing its air gap

P_a : accelerating power which accounts for any unbalance between those two quantities

Usually, rotational losses and armature $|I|^2R$ losses are neglected and P_m and P_e are thought the power supplied by the prime mover and the electrical power output, respectively.

The coefficient $J\omega_m$ is the angular momentum of the rotor. In machine data supplied for stability studies another constant related to inertia is often encountered. This is called H constant, which is defined by

$$H = \frac{\frac{1}{2}J\omega^2{}_m}{S_{mach}} \qquad \text{MJ / MVA} \tag{2.6}$$

where S_{mach} is the three-phase rating of the machine in megavoltamperes. Solving for $J\omega_m$ and substituting in equation 2.5. The equation can then be expressed using p.u. quantities as follows,

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_a = P_m - P_e \qquad \text{p.u.} \tag{2.7}$$

Equation 2.7, called the swing equation of the machine, is the fundamental equation which governs the rotational dynamics of the synchronous machine in stability studies. It is a second order differential equation, which can be written as the two first-order differential equations

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = P_m - P_e \tag{2.8}$$

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{2.9}$$

in which ω, ω_s, and δ involve electrical radians or electrical degrees.

When the swing equation is solved, the expression for δ as a function of time is obtained. A graph of the solution is called the swing curve of the machine and inspection of the swing curve of all the machines of the system will show whether the machines remain in synchronism after a disturbance.

2.3 Machine Equations

2.3.1 Synchronous Machines

In transient stability studies, particularly those involving short periods of analysis in the order of a second or less, a synchronous machine can be represented by a voltage source, behind the transient impedance, that is constant in magnitude but changes its angular position. This representation neglects the effect of saliency and assumes constant flux linkages and a small change in speed. The voltage behind the transient reactance is determined from [2]

$$E' = E_t + r_a I_t + jx'_d I_t \tag{2.10}$$

where

E' : voltage behind the transient reactance

E_t : machine terminal voltage

I_t : machine terminal current

r_a : armature resistance

x'_d : transient reactance

The representation of the synchronous machine used for network solutions and the corresponding phasor diagram are shown in figure 2.1.

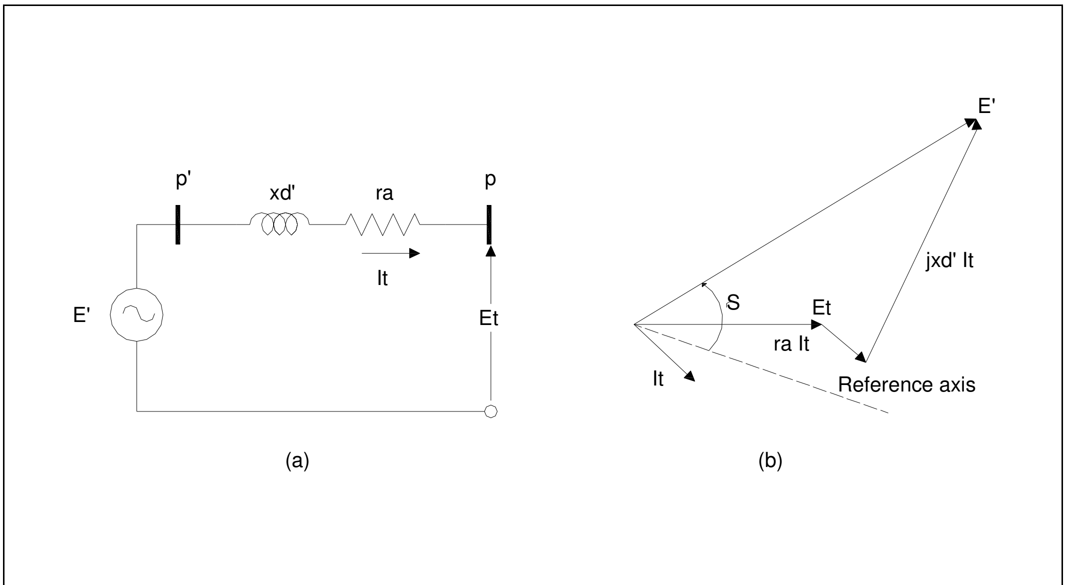


Figure 2.1 Simplified representation of a synchronous machine (a) Equivalent circuit (b) Phasor diagram

2.3.1.1 Effects Of Subtransient Circuits

In transient stability study, time period of analysis is in the order of a second and includes subtransient and transient period. The first five cycles (i.e. 0 to 100 ms) of this period is subtransient period and remaining part is transient period. In this work period of analysis is considered as transient period and synchronous machines are represented by a constant voltage source behind the transient reactance during the time period of analysis. This representation neglects the effect of saliency and assumes constant flux linkages and a small change in speed. Subtransient period is not considered because the time constant of subtransient period is very small compared to the study period, and hence the assumption of constant rotor flux linkage of all rotor circuits, including the subtransient circuits is not reasonable. As a result such a constant flux linkage model would not be generally acceptable for stability studies. [8]

2.3.2 Induction Machines

Induction motors are used extensively in industrial processes and can have significant effects on the transient response of a power system. In power system transient stability studies loads, including induction motors, usually can be represented adequately by shunt impedances.

2.4 Power System Equations

2.4.1 Representation of Loads

Power system loads, other than motors represented by equivalent circuit, can be treated in several ways during the transient period. The commonly used representations are either static impedance or admittance to ground, constant current at fixed power factor, constant real and reactive power, or a combination of these representations. Static admittance representation is used in our works. [2]

The static admittance y_{p0}, used to represent the load at bus p is

$$y_{p0} = g_{p0} + jb_{p0} \tag{2.11}$$

$$g_{p0} + jb_{p0} = \frac{S^{*}_{Lp}}{E_p E^{*}_{p}} \tag{2.12}$$

where, E_p is the calculated bus voltage and S^*_{p0} is the bus load power. Separating the real and imaginary components of equation 2.12,

$$g_{p0} = \frac{P_{Lp}}{e_p^2 + f_p^2} \quad \text{and} \quad b_{p0} = \frac{-Q_{Lp}}{e_p^2 + f_p^2} \tag{2.13}$$

where P_{Lp} and Q_{Lp} are the scheduled bus loads

2.4.2 Network Equations

The network equations describe the performance of the network during a transient period. In transient stability studies network equations represented in the bus frame of reference. In this model by the use of Thevenin theorem a generator is represented as a new bus behind the transient reactance. Using the bus admittance matrix, the voltage equation for bus p is [2]

$$E_p = \left(\frac{1}{Y_{pp}}\right)\frac{\left(P_p - jQ_p\right)}{E^*{}_p} - \sum_{\substack{q=1 \\ q \neq p}}^{n}\left(\frac{Y_{pq}}{Y_{pp}}\right)E_q \tag{2.14}$$

where Y_{pp} and Y_{pq} are the diagonal and the off-diagonal elements of the bus admittance matrix respectively. When the load at bus p is represented by a static admittance to ground, the injected current at the bus is zero and therefore

$$\left(\frac{1}{Y_{pp}}\right)\frac{\left(P_p - jQ_p\right)}{\left(E^k{}_p\right)^*} = 0 \tag{2.15}$$

In using equation 2.14 to describe the performance of the network for a transient analysis, the diagonal elements of the bus admittance matrix must be modified to include the effects of the equivalent elements required to represent synchronous machines and loads. The diagonal elements Y_{pp} must be modified for the new elements.

$$Y_{pp} = y_{p0} + y_{pp'} + \sum_{p=1}^{n} Y_{pq} \tag{2.16}$$

where y_{p0} is the static admittance representing the load and $y_{pp'}$ is the machine equivalent admittance between new generator bus p' and bus p. By using Gauss-Seidel iterative method, equations of the network are represented as follow

$$E_p^{k+1} = -\sum_{q=1}^{p-1}\left(\frac{Y_{pq}}{Y_{pp}}\right)E_q^{k+1} - \sum_{q=p+1}^{n}\left(\frac{Y_{pq}}{Y_{pp}}\right)E_q^{k} - \sum_{i=1}^{m}\frac{y_{pp'}}{Y_{pp}}E_i' \tag{2.17}$$

where E'_l is the voltages of the new buses and equal to the machine voltages behind their transient reactances. The upper superscript k indicates the iteration count. The initial bus voltages (E_q^k) are obtained from the load flow solution prior to the disturbance. The initial voltages for the new buses are obtained from the equivalent circuit representing the machines. Subsequent voltages for these buses are calculated from the differential equations describing the performance of the machines.

During the iterative calculation the magnitude of the bus voltages behind the machine equivalent admittances are held constant. If a three-phase fault is simulated, the voltage of the faulted bus is set to zero and held constant.

2.5 Solution techniques

2.5.1 Preliminary Calculations

The first step in a transient stability study is the load flow calculation to obtain the system conditions prior to the disturbance. Then the network data must be modified to correspond to the desired representation for the transient analysis. In addition, the machine currents prior to the disturbance are calculated from [2]

$$I_{ti} = \frac{P_{ti} - jQ_{ti}}{E_{ti}^{*}}$$

$$i = 1, 2, 3, \ldots, m \tag{2.18}$$

where m is the number of machine and P_{ti} and Q_{ti} are the scheduled or calculated machine real and reactive terminal powers. The calculated power for the machine at the slack bus and the terminal voltages are obtained from the initial load flow solution. Finally, the voltages behind the machine impedances must be calculated.

When the machine i is represented by a voltage source of constant magnitude behind the transient reactance, the voltage is obtained from

$$E'_{i(0)} = E_{ti} + r_a I_{ti} + jx'_{di} I_{ti} \tag{2.19}$$

where

$$E'_{i(0)} = e'_{i(0)} + jf'_{i(0)} \tag{2.20}$$

and $E'_{i(0)}$ is the initial value used in the solution of the differential equations. The initial internal voltage angle is

$$\delta_{i(0)} = \tan^{-1} \frac{f'_{i(0)}}{e'_{i(0)}} \tag{2.21}$$

The initial speed $\omega_{i(0)}$ in radians per second is equal to $2\pi f$ where f is the frequency in cycles per second. The initial mechanical power input $P_{mi(0)}$ is equal to the electrical air-gap power P_{ei} prior to the disturbance which can be obtained from

$$P_{ei} = P_{ti} + |I_{ti}|^2 r_{ai} \tag{2.22}$$

where $|I_{ti}|^2 r_{ai}$ represents the stator losses.

The next step is to change the system parameters to simulate a disturbance. Loss of a generation, load, or transmission facilities can be simulated by removing the appropriate elements from the network. A three-phase fault can be simulated by setting the voltage at the faulted bus to zero. Then, the modified network equations are solved to obtain the system conditions at the instant after the disturbance occurs.

The techniques described in section 2.4.2 can be employed to obtain the new bus voltages for the network. In the iterative solution, however, the buses behind the machine impedances are treated differently depending on the machine representation. When the machine represented by a voltage of constant magnitude behind transient reactance, the internal machine bus voltage is held fixed during the entire iterative process. The machine currents, during the fault, are calculated from the equation,

$$I_{ti} = (E'_i - E_{ti})y_{pi} \tag{2.23}$$

When the network solution has been obtained, the machine terminal current becomes the initial value for the solution of the differential equations. I_{ti} used to calculate the initial machine air-gap power from

$$P_{ei(0)} = \mathrm{Re}\left(I_{ti(0)}\, E'^{*}_{i(0)}\right) \tag{2.24}$$

when the magnitude of the voltage in behind transient reactance is held fixed

2.5.2. Modified Euler Method

When a machine is represented by a voltage of constant magnitude behind the transient reactance, it is necessary to solve the two first- order differential equations to obtain the changes in the internal voltage angle δ, and machine speed ω_i. Thus for a m machine problem where all machines are represented in the simplified manner, it is necessary to solve the 2m simultaneous differential equations. These equations are

$$\frac{d\delta_i}{dt} = \omega_{i(t)} - 2\pi f$$

$$\frac{d\omega_i}{dt} = \frac{\pi f}{H_i}\left(P_{mi} - P_{ei(t}))\right) \qquad i=1, 2, \ldots\ldots, m \qquad (2.25)$$

In this work, P_m is considered constant at given operation condition. This assumption is a fair one for generators even though input from the prime mover is controlled by governors. Governors do not act until after a change in speed is sensed, and so they are not considered effective during the time period in which rotor dynamics are of interest in our stability studies. As a result, P_{mi} remains constant and

$$P_{mi} = P_{mi(0)} \qquad (2.26)$$

For the solution of differential equations, different methods can be applied in this work, here the modified Euler method is applied. In the application of the modified Euler method the initial estimates of the internal voltage angles and machine speeds at time t+Δt are obtained from

$$\delta^{(0)}{}_{i(t+\Delta t)} = \delta^{(1)}{}_{i(t)} + \frac{d\delta_i}{dt}|_{(t)}\ \Delta t$$

$$\omega^{(0)}{}_{i(t+\Delta t)} = \omega^{(1)}{}_{i(t)} + \frac{d\omega_i}{dt}|_{(t)}\ \Delta t \qquad i = 1,2, \ldots, m \qquad (2.27)$$

where the derivatives are evaluated from equations 2.25 and $P_{ei(t)}$ are the machine powers at time t. When t=0, the machine powers $P_{ei(0)}$ are obtained from the network solution at the instant after the disturbance occurs.

Second estimates are obtained by evaluating the derivatives at time t+Δt. This requires that initial estimates be determined for the machine powers at time t+ Δt. These powers are obtained by calculating new components of the internal voltage from

$$e'^{(0)}_{i(t+\Delta t)} = |E'_i| \cos \delta^{(0)}_{i(t+\Delta t)}$$
$$f'^{(0)}_{i(t+\Delta t)} = |E'_i| \sin \delta^{(0)}_{i(t+\Delta t)} \quad (2.28)$$

Then a network solution is obtained holding fixed the voltage at the internal machine buses. When there is three-phase fault on bus f, the voltage E_f also is held fixed at zero. With the calculated bus voltages and the internal voltages, machines currents can be calculated from

$$I^{(0)}_{ti(t+\Delta t)} = \left(E'^{(0)}_{i(t+\Delta t)} - E^{(0)}_{ti(t+\Delta t)}\right) \frac{1}{r_{ai} + jx'_{di}} \quad (2.29)$$

and the machines powers from

$$P^{(0)}_{ei(t+\Delta t)} = \mathrm{Re}\left\{I^{(0)}_{ti(t+\Delta t)} \left(E'^{(0)}_{i(t+\Delta t)}\right)^*\right\} \quad (2.30)$$

The second estimates for the internal voltage angles and machine speeds are obtained from

$$\delta^{(1)}_{i(t+\Delta t)} = \delta^{(1)}_{i(t)} + \left(\frac{\frac{d\delta_i}{dt}\Big|_{(t)} + \frac{d\delta_i}{dt}\Big|_{(t+\Delta t)}}{2} \right) \Delta t$$

$$\omega^{(1)}_{i(t+\Delta t)} = \omega^{(1)}_{i(t)} + \left(\frac{\frac{d\omega_i}{dt}\Big|_{(t)} + \frac{d\omega_i}{dt}\Big|_{(t+\Delta t)}}{2} \right) \Delta t \qquad i = 1,2, \ldots, m \quad (2.31)$$

where

$$\frac{d\delta_i}{dt}\Big|_{(t+\Delta t)} = \omega^{(0)}{}_{i(t+\Delta t)} - 2\pi f$$

$$\frac{d\omega_i}{dt}\Big|_{(t+\Delta t)} = \frac{\pi f}{H_i}\left(P_{mi} - P^{(0)}{}_{ei(t+\Delta t)}\right) \tag{2.32}$$

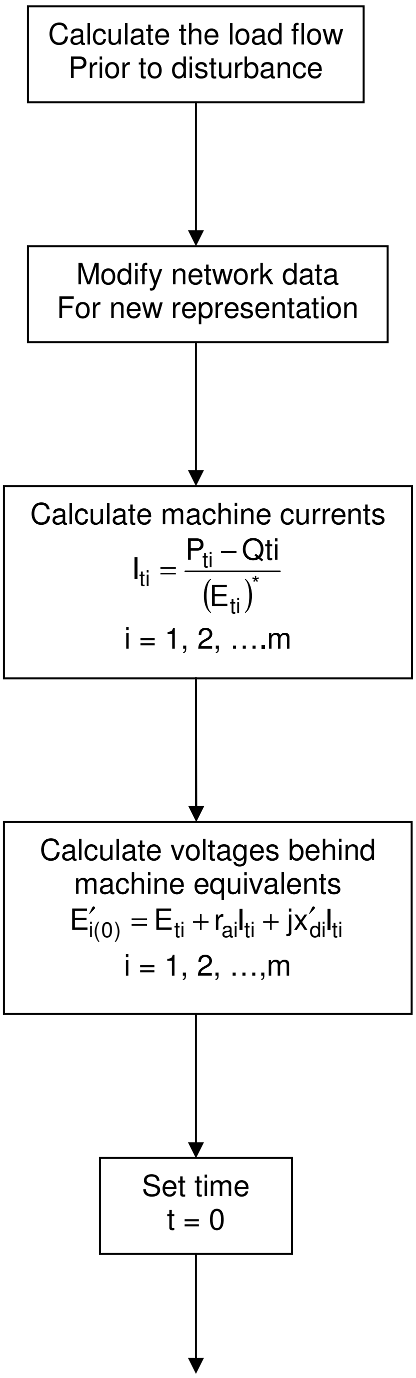
The final voltages at time t+Δt for the time internal machine buses are

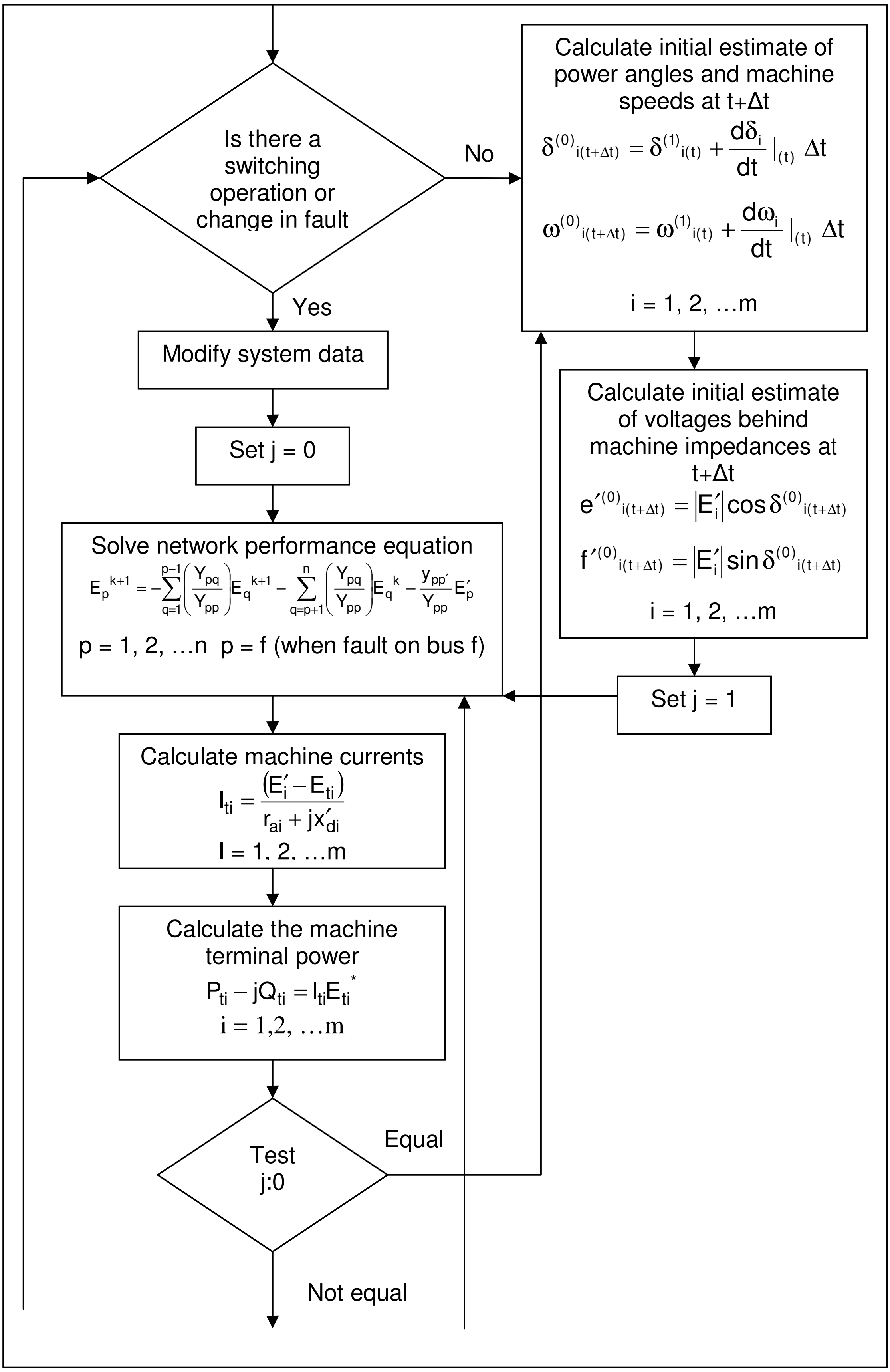
$$e'^{(1)}{}_{i(t+\Delta t)} = |E'_i| \cos \delta^{(1)}{}_{i(t+\Delta t)}$$

$$f'^{(1)}{}_{i(t+\Delta t)} = |E'_i| \sin \delta^{(1)}{}_{i(t+\Delta t)} \qquad i = 1, 2, \ldots, m \tag{2.33}$$

Then the network equations are solved again to obtain the final system voltages at time t+Δt. Voltages are checked for convergence. If voltages do not converge to the desired value, iteration is repeated for same time step. After the iteration converge to the desired value, bus voltages are used along with the internal voltages to obtain the machine currents, powers and network power flows. The time is advanced by Δt and a test is made to determine if a switching operation is to be effected or the status of the fault is to be changed. If an operation is scheduled, the appropriate changes are made in the network parameters or variables, or both. Then the network equations are solved to obtain system conditions at the instant after the change occurs. In this calculation the internal voltages are held fixed at the current values. Then, estimates are obtained for the next time increment. The process is repeated until t equals the maximum time $T_{(max)}$ specified for the study.

The sequence of steps for transient analysis by the modified Euler method and the network solution by the Gauss-Seidel iterative method using Y_{BUS} is shown in Figure2.2. Shown also are the main steps of the preliminary calculations.


Calculate the load flow
Prior to disturbance
Modify network data
For new representation
Calculate machine currents
$I_{ti} = \frac{P_{ti} - Qti}{(E_{ti})^*}$
i = 1, 2, ….m
Calculate voltages behind
machine equivalents
$E'_{i(0)} = E_{ti} + r_{ai} I_{ti} + jx'_{di} I_{ti}$
i = 1, 2, …,m
Set time
t = 0


Is there a switching operation or change in fault
No
Yes
Calculate initial estimate of power angles and machine speeds at t+Δt
$\delta^{(0)}_{i(t+\Delta t)} = \delta^{(1)}_{i(t)} + \frac{d\delta_i}{dt}\Big|_{(t)} \Delta t$
$\omega^{(0)}_{i(t+\Delta t)} = \omega^{(1)}_{i(t)} + \frac{d\omega_i}{dt}\Big|_{(t)} \Delta t$
i = 1, 2, …m
Modify system data
Set j = 0
Calculate initial estimate of voltages behind machine impedances at t+Δt
$e'^{(0)}_{i(t+\Delta t)} = |E'_i| \cos \delta^{(0)}_{i(t+\Delta t)}$
$f'^{(0)}_{i(t+\Delta t)} = |E'_i| \sin \delta^{(0)}_{i(t+\Delta t)}$
i = 1, 2, …m
Solve network performance equation
$E_p^{k+1} = -\sum_{q=1}^{p-1}\left(\frac{Y_{pq}}{Y_{pp}}\right)E_q^{k+1} - \sum_{q=p+1}^{n}\left(\frac{Y_{pq}}{Y_{pp}}\right)E_q^{k} - \frac{y_{pp'}}{Y_{pp}}E'_p$
p = 1, 2, …n p = f (when fault on bus f)
Set j = 1
Calculate machine currents
$I_{ti} = \frac{(E'_i - E_{ti})}{r_{ai} + jx'_{di}}$
I = 1, 2, …m
Calculate the machine terminal power
$P_{ti} - jQ_{ti} = I_{ti}E_{ti}^{*}$
i = 1,2, …m
Test j:0
Equal
Not equal

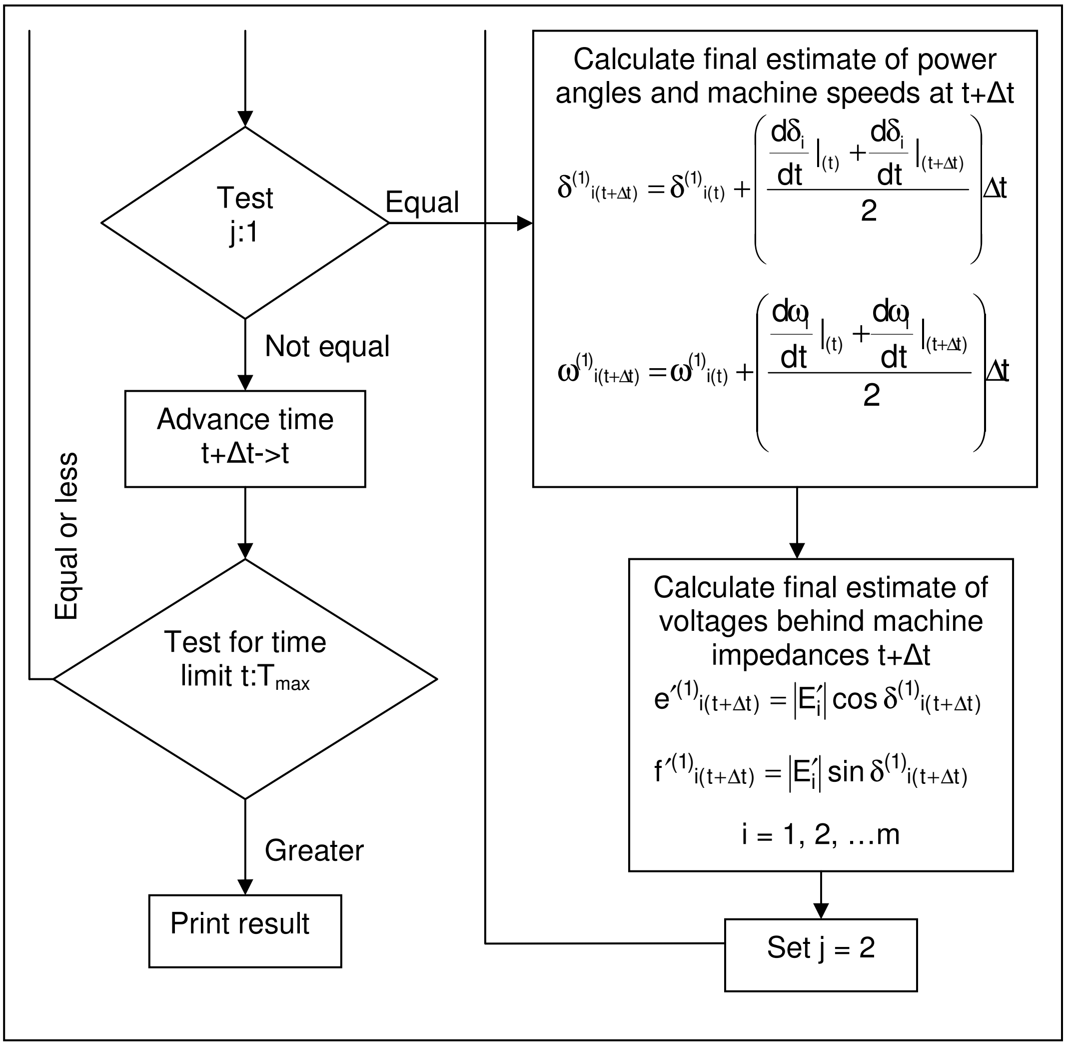


Figure 2.2 Transient calculations using the modified Euler method

2.6 Computer Program Application For Transient Stability Studies

The effects of a three phase fault on bus 2 for a duration of 0,1 sec is determined on the sample system shown in Figure 2.3 by computer program.[2]

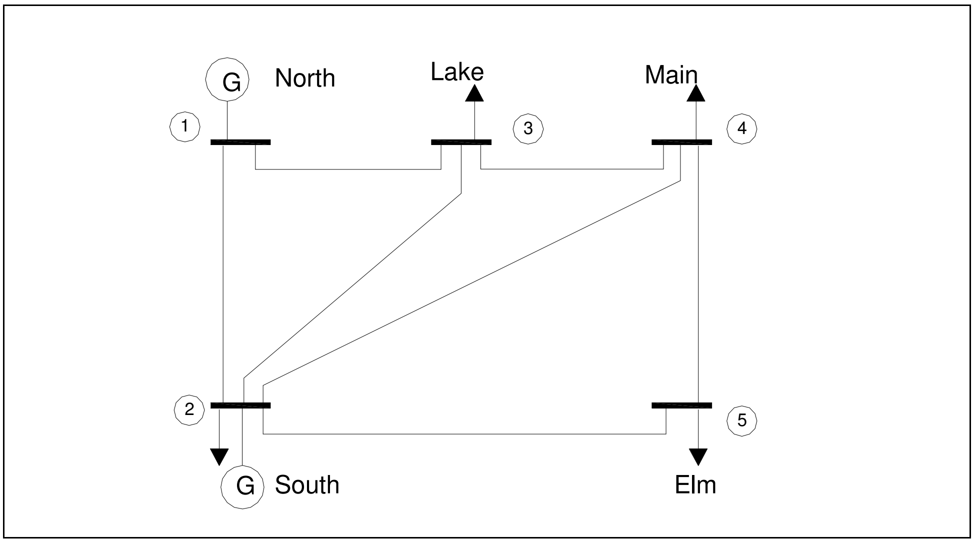


Figure 2.3 Sample system for transient stability application.

Table 2.1 Bus voltages, generation, and loads from load flow calculation prior to fault.

Bus code p	Bus voltages E_p	Generation		Load	
		Megawatts	Megavars	Megawatts	Megavars
1	1.06000+j0.0	129.565	-7.480	0.0	0.0
2	1.04621-j0.05128	40.0	30.0	20.0	10.0
3	1.02032-j0.08920	0.0	0.0	45.0	15.0
4	1.01917-j0.09506	0.0	0.0	40.0	5.0
5	1.01209-j0.10906	0.0	0.0	60.0	10.0

Table 2.2 Inertia constants, direct-axis transient reactances, and equivalent admittance for generators of sample system.

Bus code p-i	Inertia Constant H	Direct-axis transient reactance x'_d	Equivalent admittance
1-6	50.0	0.25	0.0-j4.00000
2-7	1.0	1.50	0.0-j0.66667

Computer result for the sample system is shown in Figure 2.4 The system is stable for this disturbance. Because the important factor here is the angles difference between machines. It is seen from Figure 2.4 the angle differences are small and the system settles to a new angle.

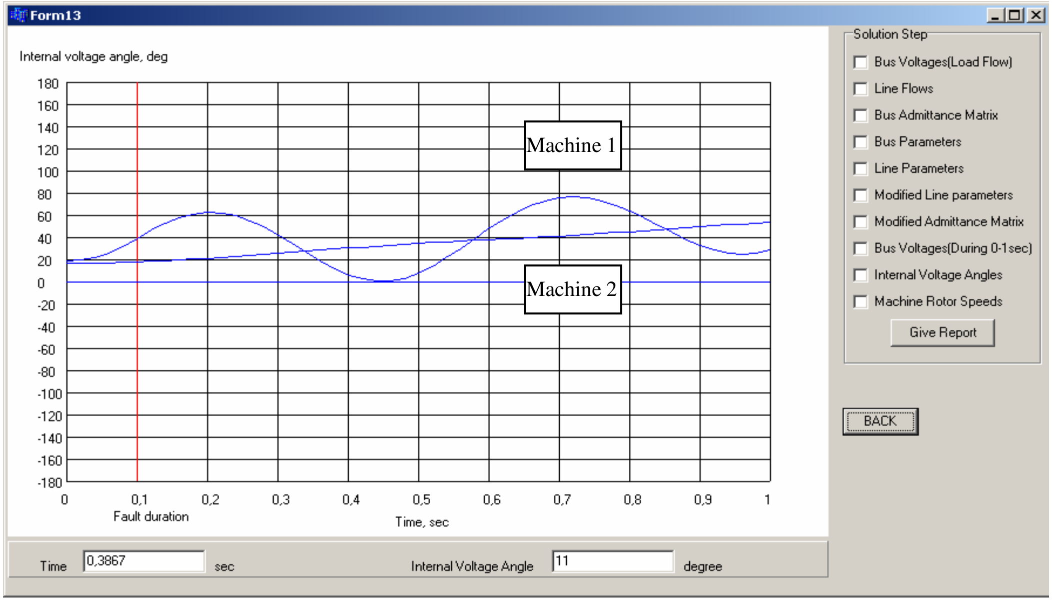


Figure 2.4 Internal voltage angle of machine with respect to time for a fault duration of 0.1 sec.

Same application repeated for the fault duration of 0.2 sec and the result is shown in Figure 2.5. In this case the system is unstable. Because the rotor angle differences is increasing continuously.

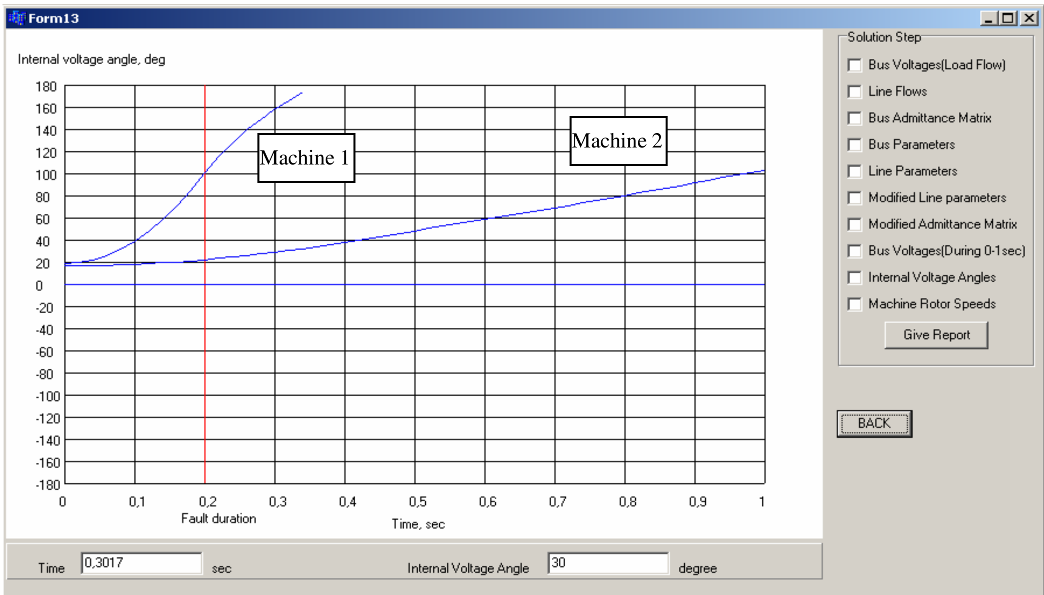


Figure 2.5 Internal voltage angle of machine with respect to time for a fault duration of 0.2 sec.

CHAPTER 3

BEFOREHAND OBTAINING A SAFETY OPERATION CONDITION BY ADJUSTING GENERATOR'S ROTOR ANGLES WITH DAILY LOAD CURVES IN TRANSIENT STABILITY

3.1 Introduction

Today, energy consumption is increasing in parallel with growing economy of the countries and technological developments. In order to keep on this growing, an interconnected power system with hundreds of machine must be designed and operated correctly. At this point, stability of power system becomes more important in order to provide continuous electrical service during operation and enlarging of the power system to overcome severest contingency i.e.

In this chapter, a new transient stability control method is introduced. The aim of this method is to determine the contingencies beforehand and then, prevent them by applying the control method. In order to determine the contingencies daily load curves are used. Proposed control method utilizes the relationship between critical clearing times and generator rotor angles. This relationship is first studied on a single machine and infinite bus system and then, extended to the multimachine case. By the means of this relationship whole power system and all contingencies can be observed and more stable operating point is carried out by generator output power rescheduling and terminal voltage control.

3.2 Relationship Between Critical Clearing Angle And Generator Rotor Angle

3.2.1 One Machine to Infinite Bus System

One machine to infinite bus system is used for determining the relationship between critical clearing time and the generator rotor angle. This system consists of generator, transformer, double transmission line and infinite bus as shown in Figure 3.1. The generator model used here is the simplified generator model as explained in section 2.3.1. The resistance of the transmission line and the control systems (for example, AVR and Governor) are neglected.

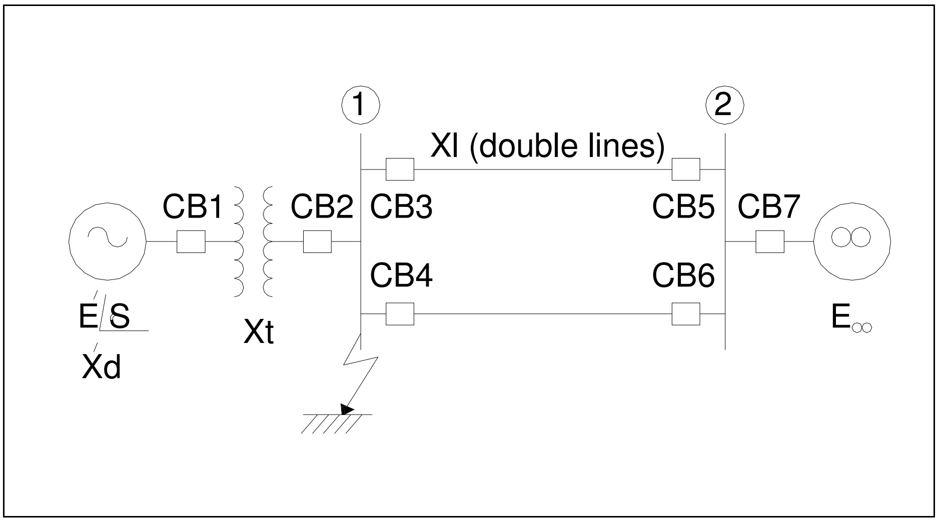


Figure 3.1 One machine to infinite system

The proposed transient stability preventive control uses a relationship between critical clearing time and the generator rotor angle. The sample system data used in during the inspection of relationship is as follows.

Table 3.1 Sample one machine to infinite bus system data

Bus 1 voltage	Bus 2 voltage	X'_d	X_t	X_l	Generator output power
1.0 p.u.	1.0 p.u.	0.2 p.u	0.1 p.u	0.4 p.u	1.0 p.u

where,

Xt : reactance of transformers

X_l : reactance of double circuit lines

Xd' : transient reactance

Fault can be occurred in three regions. Left side of the bus 1, between bus 1 and bus 2 and right side of the bus 3. For these three cases, rotor angle versus critical clearing time changes is examined.

3.2.1.1 Case 1: Fault at Bus 1

In this case a three phase to ground fault at bus 1 is considered. The fault occurs and is cleared by tripping the circuit breakers CB2, CB3 and CB4. Hence fault is effective during the operation of the circuit breaker and relay combination. The generator is operating initially at a synchronous speed with a rotor angle of δ_o and the input mechanical power Pm equals the electrical power P_o. At the instant of the fault electrical power is dropped to zero but mechanical input power doesn't change. Power-angle curve of the system is shown in Figure 3.2. [1]

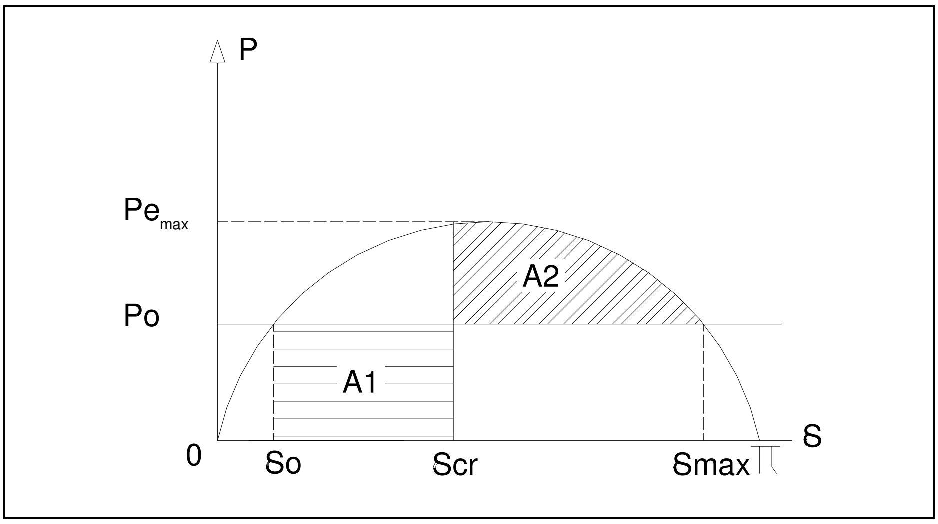


Figure 3.2 Power-angle curve for case 1

where,

$$Pe_{max} = \frac{E' E_{\infty}}{X_t + X_l + Xd'} \quad (3.1)$$

$$\delta_0 = \arcsin\left(\frac{P_0}{Pe_{max}}\right) \quad (3.2)$$

E' : voltage behind the transient reactance

E_{∞} : voltage of infinite bus

δ_o : rotor angle before the fault

δ_{cr} : critical clearing angle

Equal area criterion is applied to the system for obtaining both critical clearing angle and critical clearing time. This criterion states that the kinetic energy added to the rotor following a fault must be removed after the fault in order to restore the rotor to synchronous speed. Therefore, the acceleration area denoted by A1 and deceleration area denoted by A2 must be equal.[1]

$$A1 = \int_{\delta_0}^{\delta_{cr}} P_m d\delta = P_m (\delta_{cr} - \delta_0) \quad (3.3)$$

$$A2 = \int_{\delta_{cr}}^{\delta_{max}} (P_{max} \sin\delta - P_m) d\delta = P_{max}(\cos\delta_{cr} - \cos\delta_{max}) - P_m(\delta_{max} - \delta_{cr}) \quad (3.4)$$

Equating the expressions for A1 and A2 and solving for δ_{cr}. The expression for critical clearing angle is obtained as follow,

$$\delta_{cr} = \cos^{-1}[(\pi - 2\delta_o)\sin\delta_o - \cos\delta_o] \quad (3.5)$$

Integration of swing equation with respect to time and for $t = t_{cr}$ gives,

$$\delta_{cr} = \frac{\omega_s P_m}{4H} t_{cr}^2 + \delta_0 \quad (3.6)$$

and substitute the equation 3.5. in equation 3.6 yields,

$$t_{cr} = \sqrt{\frac{4H}{\omega_s P_m}\left(\cos^{-1}[(\pi - 2\delta_o)\sin\delta_o - \cos\delta_o] - \delta_o \right)} \tag{3.7}$$

From equations 3.5 and 3.7 as it is seen, when P_m is changed, δ_o and critical clearing time are also changed. These changes are examined by increasing P_m from $0.8P_m$ to $1.2P_m$ in steps of 4% P_m by using computer program [5],[4]. The results are given in Table 3.2 and graphic of rotor angle versus critical clearing time is shown in Figure 3.3.

Table 3.2 Computer program output for case 1

Generator Input Power (pu)	Generator Rotor Angle (Degree)	Critical Clearing Time (s)
0,84000	23,57980	0,26930
0,88000	24,77620	0,25660
0,92000	25,98420	0,24455
0,96000	27,20480	0,23307
1,00000	28,43890	0,22211
1,04000	29,68760	0,21161
1,08000	30,95190	0,20151
1,12000	32,23330	0,19179
1,16000	33,53300	0,18239
1,20000	34,85250	0,17329

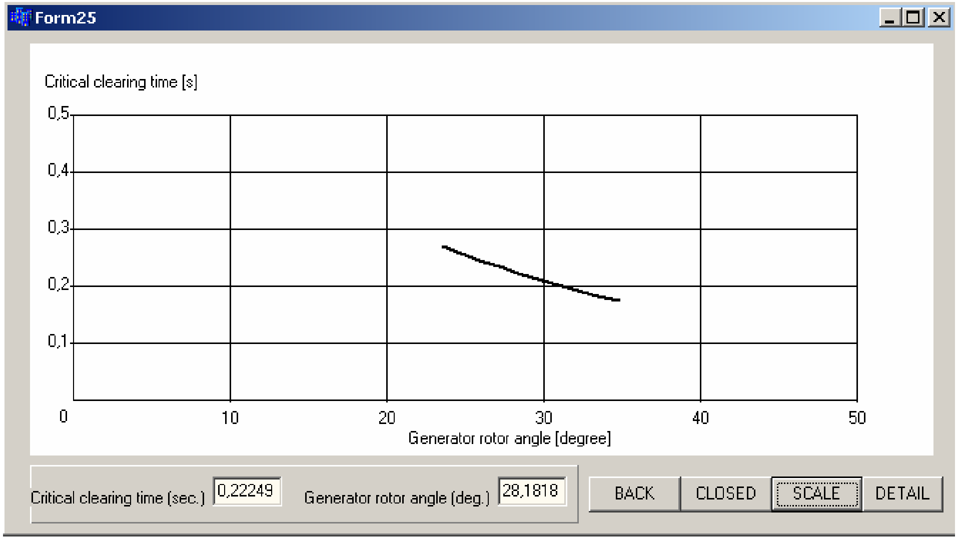


Figure 3.3 Critical clearing time versus generator rotor angle graphic.

It is observed that for this case critical clearing time variation is almost linear.

3.2.1.2 Case 2: Fault between Bus 1 and Bus 2

A three phase to ground fault between bus 1 and bus 2 is considered in this case. The fault is cleared by tripping the circuit breakers at both ends on the line. Hence power is transmitted through one line only. Power-angle curve of the system is shown in Figure 3.4. [1]

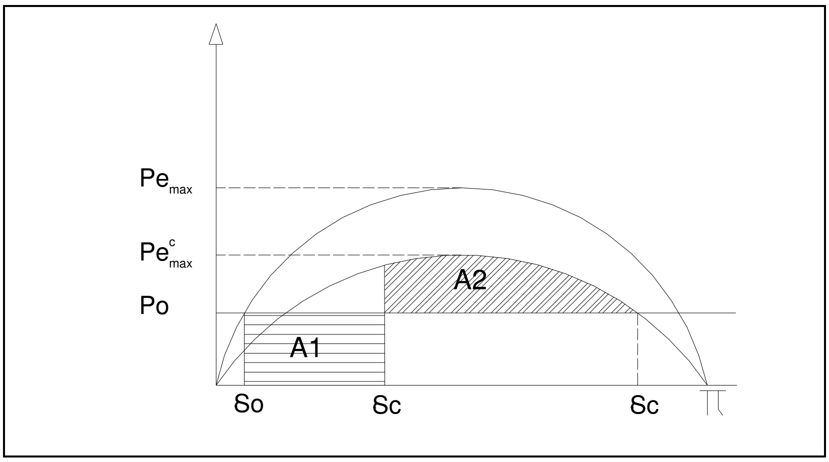


Figure 3.4 Power-angle curve for case 2

where,

$Pe^{pf}{}_{max}$: maximum generator output after post fault

$Pe^{df}{}_{max}$: maximum generator output during fault.

By utilizing the figure 3.4, expressions for A1 and A2 are written as follow,

$$A1 = \int_{\delta_0}^{\delta_{cr}} \left(P_0 - Pe^{df}{}_{max} \sin\delta\right) d\delta = P_0(\delta_{cr} - \delta_0) + Pe^{df}{}_{ma}(\cos\delta_{cr} - \cos\delta_0) \qquad (3.8)$$

$$A2 = \int_{\delta_{cr}}^{\delta_{max}} \left(P^{pf}{}_{max} \sin\delta - P_0\right) d\delta = P^{pf}{}_{max}(\cos\delta_{cr} - \cos\delta_{max}) - P_0(\delta_{max} - \delta_{cr}) \qquad (3.9)$$

Equating the expressions for A1 and A2 and solving for δ_{cr} [1].

$$\delta_{cr} = \cos^{-1}\left[\frac{\left(P_o(\delta_{max} - \delta_o) + Pe^{pf}{}_{max}\cos\delta_{max} - Pe^{df}{}_{max}\cos\delta_o\right)}{Pe^{pf}{}_{max} - Pe^{df}{}_{max}}\right] \qquad (3.10)$$

An explicit solution for the critical clearing time is not possible in this case. To determine the critical clearing time, the swing equation must be solved by numerical method. The swing equation to be solved is,

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H}\left(P_m - P_e{}^{df}{}_{max}\sin\delta\right) \qquad (3.11)$$

This equation is a second order differential equation. It can be written as two first order differential equation ,

$$\frac{d\omega}{dt} = \frac{\omega_s}{2H}\left(P_m - P_e{}^{df}{}_{max}\sin\delta\right) \qquad (3.12)$$

$$\frac{d\delta}{dt} = \omega - \omega_s \qquad (3.13)$$

and then, modified Euler method is applied. Predictor equations are,

$$\delta^{k+1} = \delta^{k} + \Delta t\left(\omega^{k} - \omega_{s}\right) \tag{3.14}$$

$$\omega^{k+1} = \omega^{k} + \Delta t\left[\frac{\pi f}{H}\left(P_{m} - P^{k}{}_{e}\right)\right] \tag{3.15}$$

and corrector equations are,

$$\delta^{k+1} = \delta^{k} + \Delta t\left(\omega^{k} - \omega_{s} + \omega^{k+1} - \omega_{s}\right) \tag{3.16}$$

$$\omega^{k+1} = \omega^{k} + \Delta t\left[\frac{\pi f}{H}\left(P_{m} - P^{k}{}_{e}\right) + \frac{\pi f}{H}\left(P_{m} - P^{k+1}{}_{e}\right)\right] \tag{3.17}$$

where, k is the iteration count

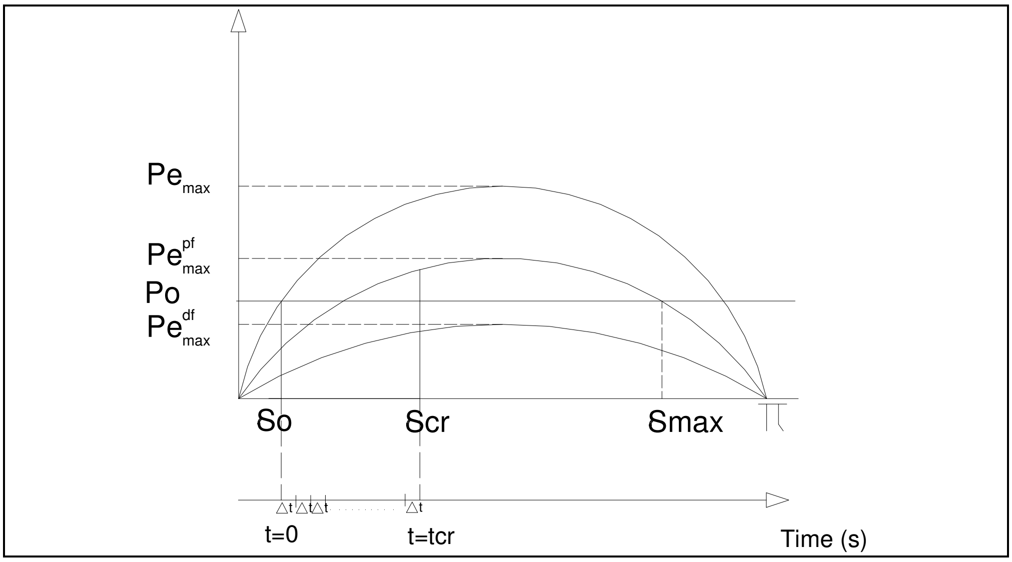
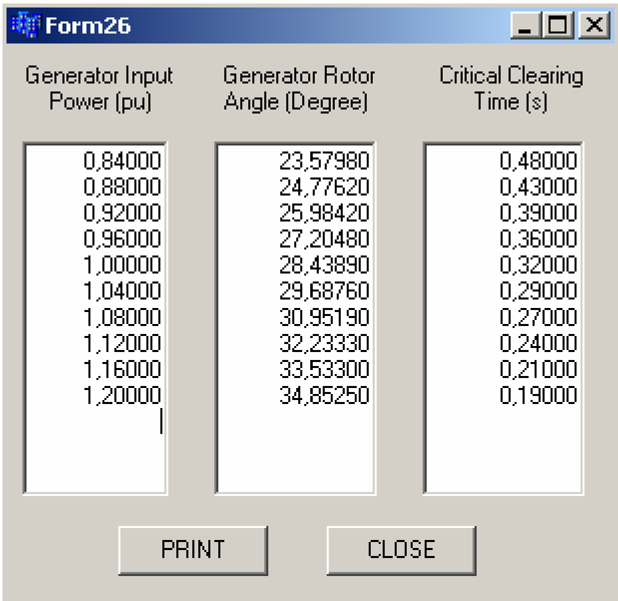


Figure 3.5 Rotor angle versus critical clearing time

By using the predictor and corrector equations swing equation is solved between upper and lower limits, i.e. from δo to δ_{cr}. Results obtained are shown in Table 3.3 and Figure 3.6.

Table 3.3 Computer program output for case 2



Generator Input Power (pu)	Generator Rotor Angle (Degree)	Critical Clearing Time (s)
0,84000	23,57980	0,48000
0,88000	24,77620	0,43000
0,92000	25,98420	0,39000
0,96000	27,20480	0,36000
1,00000	28,43890	0,32000
1,04000	29,68760	0,29000
1,08000	30,95190	0,27000
1,12000	32,23330	0,24000
1,16000	33,53300	0,21000
1,20000	34,85250	0,19000

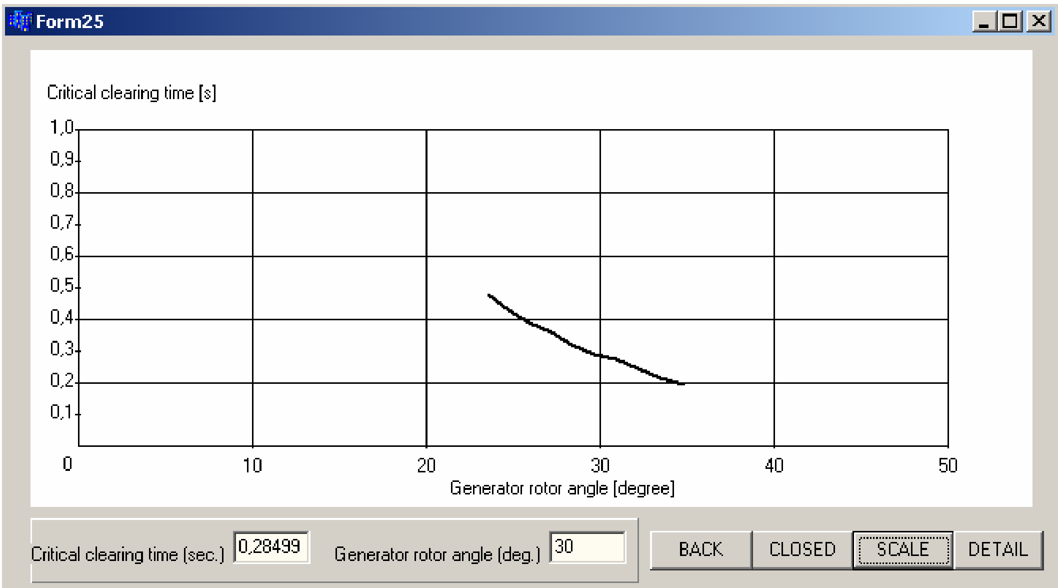


Figure 3.6 Critical clearing time versus generator rotor angle graphic.

As in case 1, critical clearing time variation is almost linear.

3.2.1.3 Case 3: Fault on Bus 2

In this case, a three phase to ground fault at bus 2 is considered. The fault occurs and is cleared by tripping the circuit breakers CB5, CB6 and CB7. Hence fault is effective during the operation of the circuit breaker and relay combination. The generator is operating initially at a synchronous speed with a rotor angle of δ_o and the input mechanical power Pm equals the electrical power P_o. At the instant of the fault electrical power is drop to zero but mechanical input power doesn't change. Power-angle curve of the system is shown in Figure 3.7. This graphic is identical in case 1.

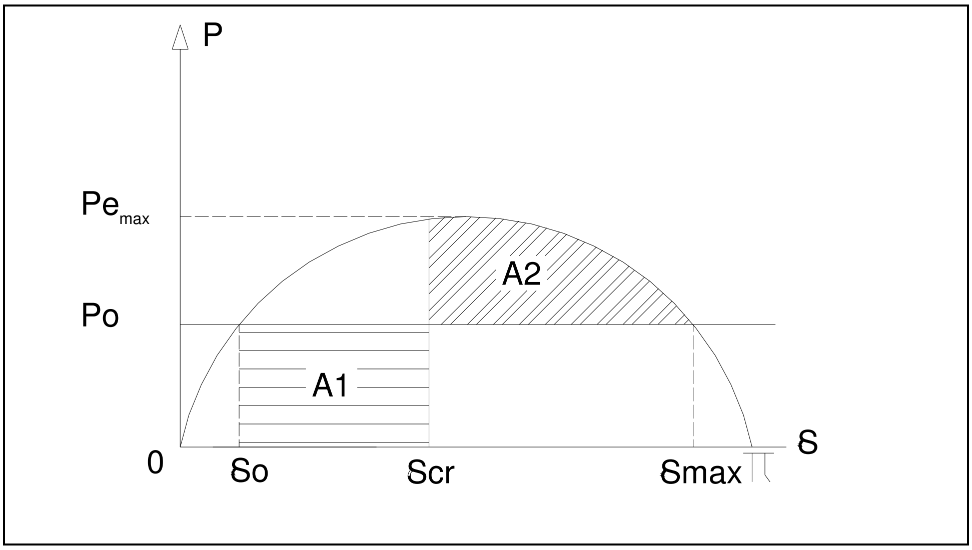


Figure 3.7 Power-angle curve for case 3

Computer programs results are same as in Table 3.2 and Figure 3.3 too. Consequently rotor angle versus critical clearing time graphic is almost linear.

3.2.1.4 Effect of Resistance

The transmission lines have resistance about 10% of its transient reactance. The same inspection is repeated by taking into the consideration of the resistance. It is observed that the changes in the generator rotor angle and the critical clearing times are about 1%. This result shows that neglecting the resistance is not effective on the linearity. Hence, the effect of the resistance of the transmission line is neglected.

3.2.2 Multimachine System

The relationships between critical clearing angle and the generator rotor angles are shown by a simulation study using a multimachine power system. The sample system is the IEEJ EAST 10 machine system, which is shown in Figure 3.8. [3]

The contingencies are three phase to ground faults occurring at buses having generators, that is, the faults at buses 11-20. It is assumed that the fault-cleared system condition is the same as the prefault system. That is, both the loading and the stable equilibrium conditions are assumed to be the same. The initial condition of this simulation is a 75% load condition of the original data. The simulations are carried out increasing the loads 5% step by step of the original data. The relation between critical clearing angles and the generator rotor angles are shown in Figure 3.9. The relationships are again showing linear variation in multimachine case. It is seen how large the critical clearing angle changes are when the generator rotor angles are changed.

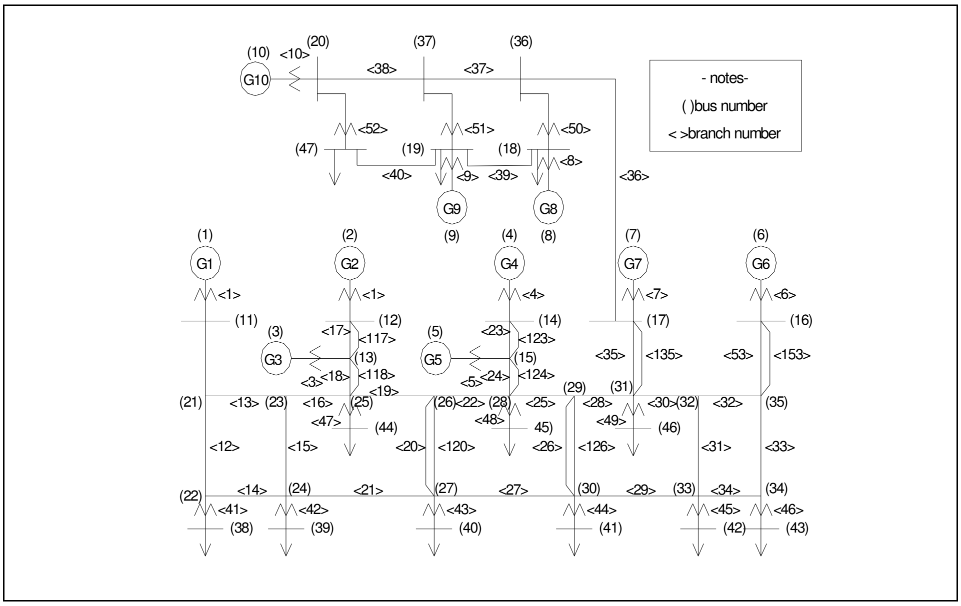


Figure 3.8 IEEJ EAST 10 machine system

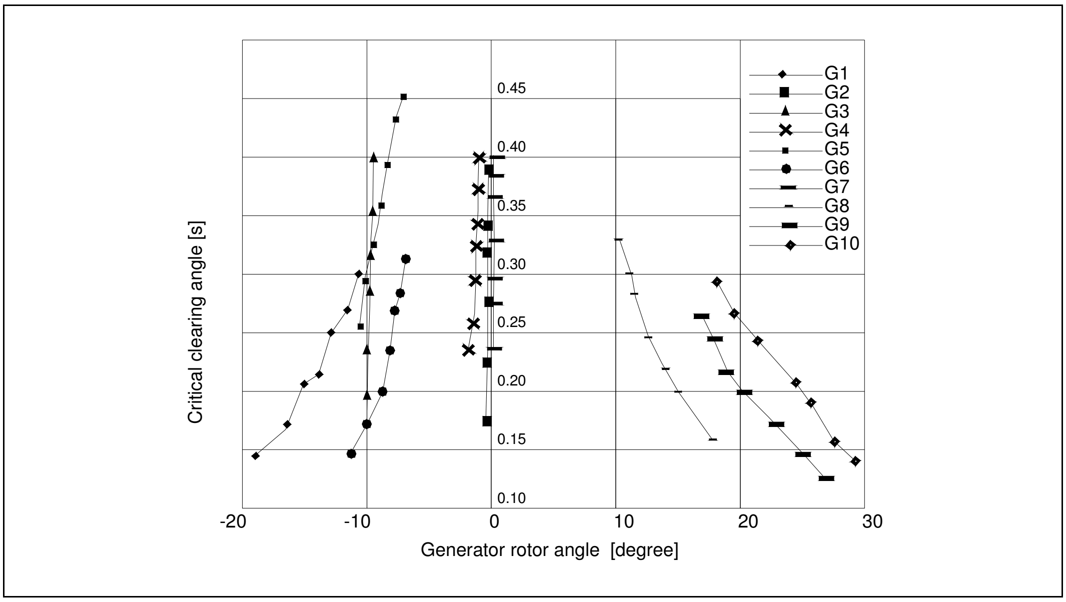


Figure 3.9 Relationships between critical clearing angles and generator rotor angles (IEEJ EAST 10 machine system)

3.3 Generator Rotor Angle Estimation

In this section, generator rotor angles are estimated for present and future condition. These values are used for preventive control method if necessary to find critical clearing time utilizing the linear relationship between critical clearing time and generator angle.

3.3.1 Generator Rotor Angle Estimation For Present Condition

Consider a generator directly connected to several transmission lines as shown in Figure 3.10. The instrumentation around the bus can be divided into injections, bus metering, and line flow measurements. Each of the measurements monitor all three phases. The following assumptions are made: [6]

1. Balanced three-phase flow conditions are present, and the system is in steady-state operation.
2. Accuracy of metering is known (i.e., the meter readings are accurate to 0.5%, 1%, etc., of the true physical value).

3. The full scale range of each meter is known, i.e., from 0 to 100 MW, 0 to 50 Mvar, etc.

4. The errors in converting the analog quantities to digital signals for the data link to the central computer are known.

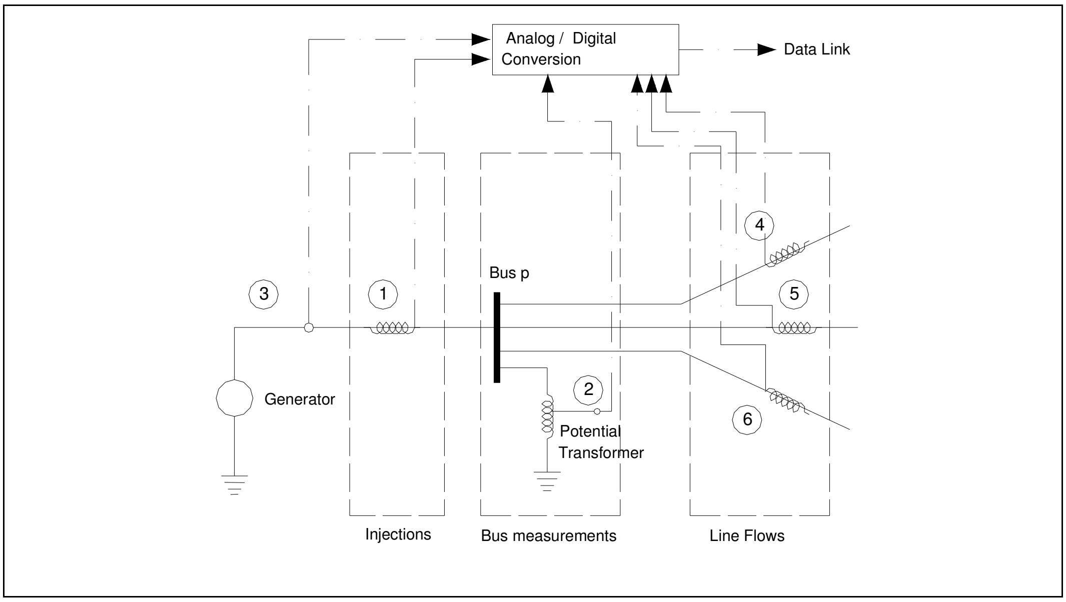


Figure 3.10 Measurements at a bus

The three phases are checked for balance, then products of instantaneous voltage and currents are obtained for scaled, limited ranges and converted into serial digital data by the remote terminal unit.

By utilizing these digital data power flow is carried out (appendix A) and we get the bus voltage and angle of load bus, angle and reactive power values for voltage controlled bus and slack bus real and reactive powers are determined. By using these values, the generator rotor angles can be obtained. Consequently, generators rotor angles for the present condition are found for all machines in the system.

3.3.2 Generator Rotor Angle Estimation For Future Load Condition

Generator output rescheduling is used for preventive control. However generator output can not be rescheduled instantaneously. It is known that rescheduling time depends on the generator characteristics and the magnitudes of the generator output changes. Therefore, a load condition every 5-10 minute should be expected.

In this proposed method, daily load curves are used to predict future condition load powers. Curves are sampled in discrete manner with a sampled time intervals of 5 minutes as shown in Figure 3.12

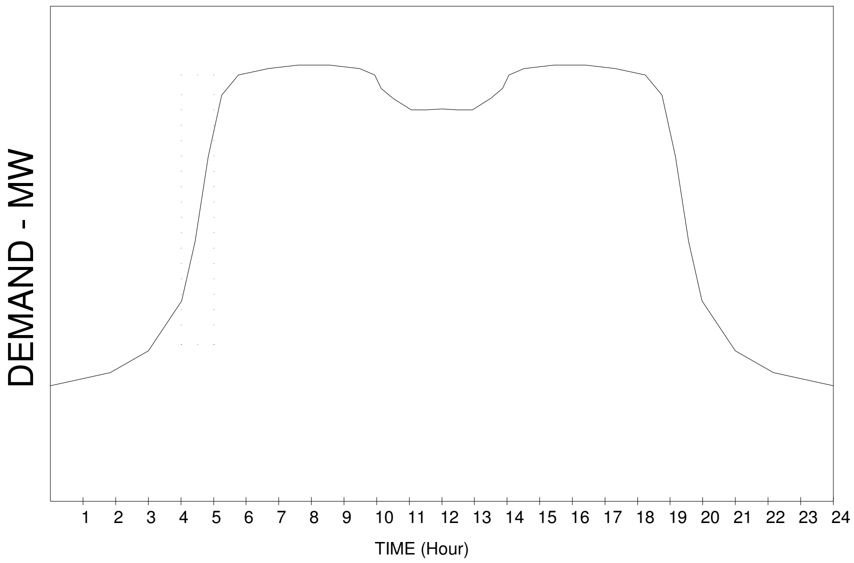


Figure 3.11 Sample daily load curve for industrial load

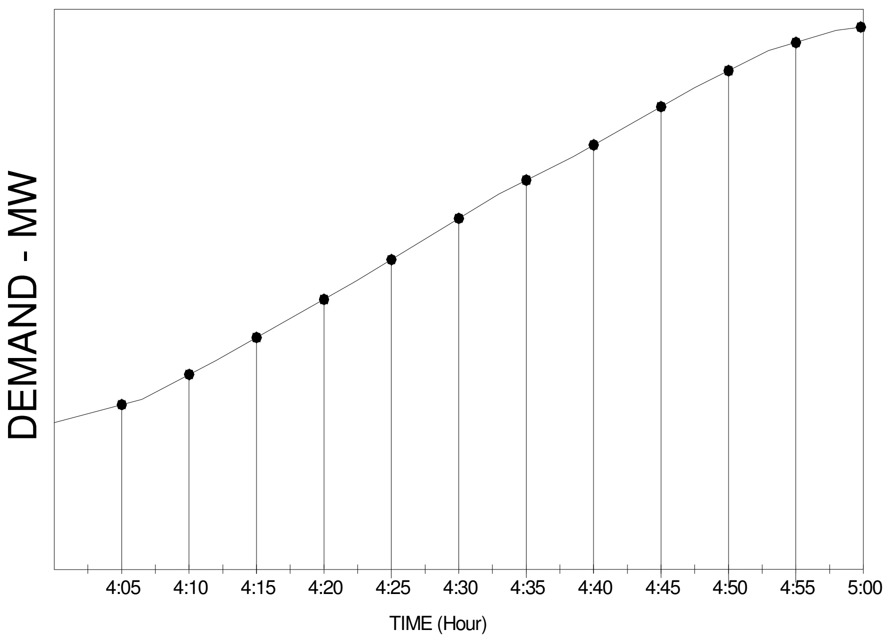


Figure 3.12 Discrete time sampling of daily load curve with 5 minute time interval

Powers, getting from the discrete time sampling are used for calculating the generator rotor angles. As in the present condition related data are entered the load flow calculations and as a result, load bus voltages and angles, voltage bus reactive powers and angles, slack bus real and reactive powers are obtained for future condition. Machine currents I_{ti}, voltage behind the transient reactance E_i and the rotor angle δ_i are calculated.

3.4 Proposed Preventive Control Method

Transient stability preventive control method is proposed in this work. This method determines the severe contingencies by using daily load curves beforehand, and then prevents them by applying a control method.

Determining the severe contingencies beforehand is very important for power system operation and also for preventive control necessity. These contingencies are the three phase to ground faults occurring at the buses having generators, because these faults are the most severe ones. In these cases if all critical clearing times are larger than the predefined values (the actual operating times of the circuit breaker and relay combination in the power system) no preventive control is necessary. If one or more of the critical clearing times are smaller than the predefined values, preventive control is necessary..[3]

This method uses the linear relationships between critical clearing times and generator rotor angles shown in section 3.2. The present system critical clearing times are calculated by using the online system and future condition critical clearing times are calculated by utilizing the daily load curves. These critical clearing times and generator rotor angles define a straight line, i.e,

$$CCT_{pd} = m(\delta_d - \delta_p) + CCT_p$$
$$m = (CCT_f - CCT_p)/(\delta_f - \delta_p) \tag{3.18}$$

where

CCT_p : Critical clearing time for present condition

CCT_f : Critical clearing time for future condition

CCT_{pd} : Predefined critical clearing time (Sum of the circuit breaker and relay operation time)

δ_p : Present condition rotor angle

δ_f : Future condition rotor angle

δ_d : Desired rotor angle after preventive control

This line (equation 3.18) can now be used for preventive control in order to calculate desired rotor angle δ_{pd}. This value is the marginal value for stability and adjusted by generator output rescheduling and generator terminal voltage control.

By the means of this method whole power system and all contingencies can be observed and more stable operating point is carried out using generator output rescheduling and generator terminal voltage control.

3.5. Estimation of Generator Outputs (P,Q)

In this section, the increment of the generator outputs are calculated by using the following equation

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|E| \end{bmatrix} \tag{3.19}$$

where, J1, J2, J3 and J4 are the entries of the Jacobian matrix. (Appendix B). They are obtained by utilizing the modified bus admittance matrix used in transient stability.

The increment in phase angles and internal voltages of the generator are

$$\Delta\delta i = \delta_f - \delta_p \tag{3.20}$$

$$\Delta E_i = E_f - E_p \tag{3.21}$$

,respectively. Hence generator outputs which are used for control method are calculated. The obtained active and reactive powers of the generators are adjusted by governor system and field circuit respectively. If its governor set point increased, the no-load frequency of the generator shifts upward. Since the frequency of the system is unchanged, the power supplied by the generator is increases. If the power supplied is constant as the field current is changed, then the reactive power is changed. By the means of governor system and field circuit the desired rotor angle is adjusted. (Appendix C)

3.6. Computer Program Application For Relationship Between Critical Clearing Angle And Generator Rotor Angle In Multimachine Case

Computer program is performed on a sample system used in section 2.6. Related values are given in Table 2.1 and Table 2.2. In this application three phase to ground fault occurring at buses having generators that is, the faults at buses having generators, that is, the faults at buses 1 and 2 are considered individually. It is assumed that the fault cleared system condition is the same as the prefault system. That is, both the loading and stable equilibrium conditions are assumed to be the same. The initial condition of the simulation is a 75% load condition of the original data. The simulations are carried out increasing the loads 5% step by step of the original data. The obtained rotor angle and critical clearing times are given in Table 3.4 and the relations between critical clearing angles and generator rotor angles are shown in Figure 3.13 and Figure 3.14.

Table 3.4. Generator rotor angles and critical clearing times

Loading	Generator 1		Generator 2	
	Rotor Angle (degree)	Critical clearing angle (sec.)	Rotor Angle (degree)	Critical clearing angle (sec.)
75%	12.349	0.258	14.607	0.238
80%	13.155	0.238	15.424	0.238
85%	13.958	0.238	16.210	0.218
90%	14.756	0.218	16.965	0.218
95%	15.550	0.218	17.690	0.198
100%	16.339	0.198	18.389	0.198

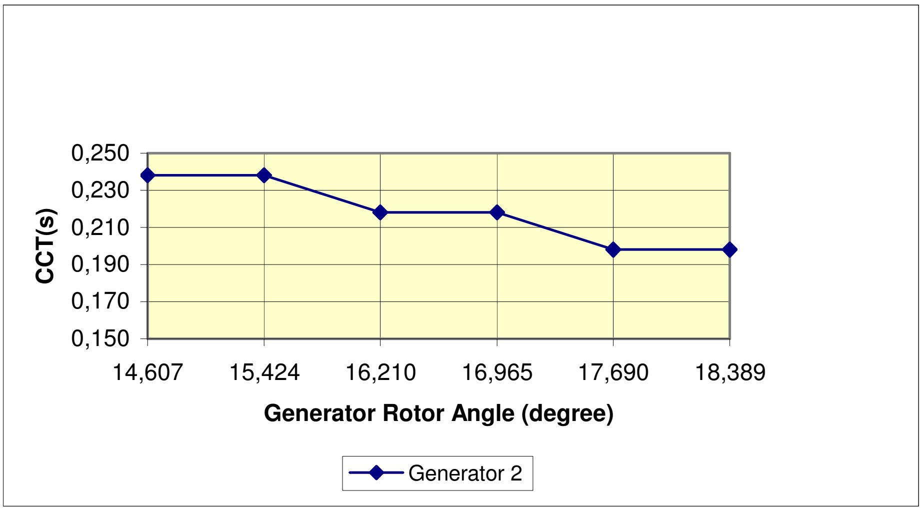


Figure 3.13 Relationship between generator 1 rotor angle and critical clearing time

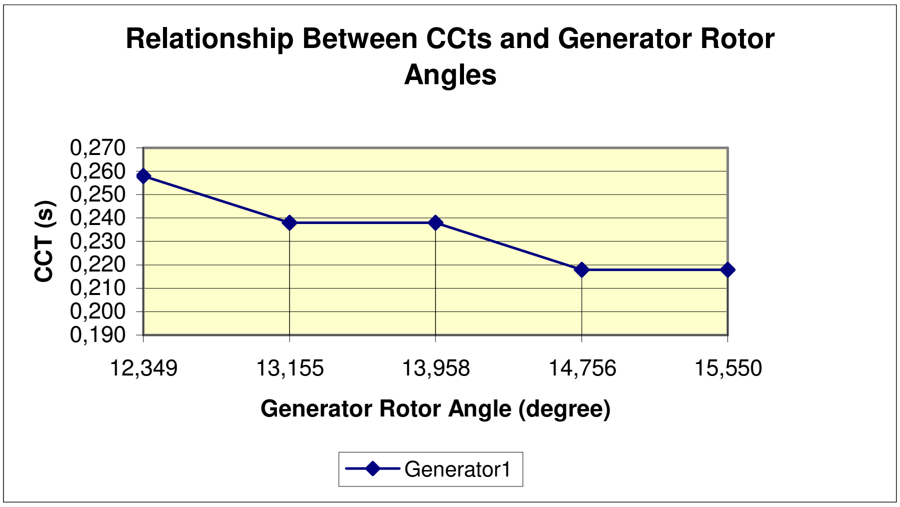


Figure 3.14 Relationship between generator 2 rotor angle and critical clearing time

In this application, it is seen that the relationships are almost linear as explained in Section 3.2.2.

CHAPTER 4

CONCLUSION

In this work, by utilizing the daily load curves a preventive control method is proposed. The aim of this method is to make all critical clearing times larger than the predefined values. Predefined values are the operation time of the relay and circuit breaker. Before the preventive method carried out, transient stability calculation must be done.

The objective of the transient stability is to determine whether or not the rotors of the machines remain in synchronism during disturbances. In order to determine the stability, power systems which consist of machines, interconnected system and loads are modelled to reflect the correct dynamic performance of the system. The synchronous machines are represented by a voltage source, in the back of transient impedance, that is constant in magnitude but changes its angular position. This representation neglects the effect of saliency and assumes constant flux linkages and a small change in speed. The loads are represented by a static admittance and networks are represented by algebraic equations. The bus admittance matrix used in network equation is modified in order to include the equivalent circuits of machines and static admittance to ground for loads to reflect the changes in the representation of the network.

A transient stability analysis is performed by combining a solution of the algebraic equations describing the network with a numerical solution of the differential equations describing the synchronous machines. Two first order differential equations are required for the simplest representation of a synchronous machine. Then, system parameters are changed to simulate a disturbance. Loss of a generation, load, or transmission facilities can be simulated by removing the appropriate elements from the network. A three-phase fault can be simulated by setting the voltage at the faulted bus to zero. Then, the modified network equations are solved by iteratively to obtain the system conditions at the instant after the disturbance occurs. The internal machine bus voltage is held fixed during the entire iterative process. When the network solution has been obtained, the machine terminal current which is used to calculate the initial machine air-gap power becomes the initial value for the solution of the differential equations. It is necessary to solve the two first- order differential equations to obtain the changes in the internal voltage angle δ, and machine speed ω_i. Thus for m machine problem where all machines are represented in the simplified manner, it is necessary to solve the 2m simultaneous differential equations. During the solution P_m is considered constant at given operation condition. This assumption is a fair one for generators even though input from the prime mover is controlled by governors. Governors do not act until after a change in speed is sensed, and so they are not considered effective during the time period in which rotor dynamics are of interest in our stability studies. As a result internal voltage angle δ and machine speed ω changes versus time is determined as explained in Section 2.6. Critical clearing times are obtained by using the internal voltage angle graphics by adjusting the fault duration at the related bus terminal.

The preventive control method deals with the relationship between the rotor angles and the critical clearing times. The relationship is first studied on a single machine infinite bus system which is consist of generator, transmission lines and infinite bus. Three phase to ground faults, that are severest ones, are considered at the different regions of the system.

At first, fault at the generator bus is considered as explained in Section 3.2.1.1. The fault occurs and is cleared by tripping the circuit breakers. Hence fault is effective during the operation of the circuit breaker and relay combination. Power-angle curve of the system is obtained, as given in Figure 3.2, then, equal area criterion is applied to the system for obtaining both critical clearing angle and critical clearing time. As it is seen from the result, when input power P_m is changed, rotor angle δ_o and critical clearing time are also changed. These changes are examined by increasing P_m from $0.8P_m$ to $1.2P_m$ in steps of 4% P_m by using computer program. The results given in Figure 3.3 show that for this case critical clearing time variation is almost linear. Then, a three phase to ground fault between bus generator bus and infinite bus is considered as explained in Section 3.2.1.2. The fault is cleared by tripping the circuit breakers at both ends on the line. Hence power is transmitted through one line only. Power-angle curve of the system is obtained, as given in Figure 3.4. An explicit solution for the critical clearing time is not possible in this case. To determine the critical clearing time, the swing equation must be solved by numerical method. For this purpose Modified Euler Method is used. Again, the results (Figure 3.6) show that for this case critical clearing time variation is again linear. Finally a three phase to ground fault at infinite bus is considered as explained in Section 3.2.1.3. Power-angle curve is same as the first case (Figure 3.7) and the results are same too. During these examinations the resistance of the transmission line is neglected. The same inspection is repeated by taking into the consideration of the resistance. It is observed that the resistance is not effective on the linearity. The results are encouraging in order to extend the study to multimachine case.

In multimachine case, a simulation study on IEE of Japan EAST 10 machine system is used. The contingencies are three phase to ground faults occurring at buses having generators. It is assumed that the fault-cleared system condition is the same as the prefault system. That is, both the loading and the stable equilibrium conditions are assumed to be the same. The initial condition of this simulation is a 75% load condition of the original data. The simulations are carried out increasing the loads 5% step by step of the original data. It is observed that the relation between critical clearing angles and the generator rotor angles show linear variation too as given in Figure 3.9.

By using these results and daily load curves a new preventive control method is proposed. This method determines the severe contingencies by using daily load curves beforehand, and then prevents them by applying a control method. Determining the severe contingencies beforehand is very important for power system operation and also for preventive control necessity. These contingencies are the three phase to ground faults occurring at the buses having generators. In these cases if all critical clearing times are larger than the predefined values no preventive control is necessary. If one or more of the critical clearing times are smaller than the predefined values, preventive control is necessary.

This method uses the linear relationships between critical clearing times and generator rotor angles. The present system critical clearing times are calculated by using the online system and future condition critical clearing times are calculated by utilizing the daily load curves. These critical clearing times and generator rotor angles define a straight line. This line is used for preventive control in order to calculate desired rotor angle δ_{pd}. This value is the marginal value for stability and adjusted by generator output rescheduling and generator terminal voltage control.

The generator outputs are estimated by using the Jacobian matrix. Its entries are obtained by using the modified bus admittance matrix used in transient stability. The obtained active and reactive powers of the generators are adjusted by governor system and field circuit, respectively.

By means of this method whole power system and all contingencies can be observed and more stable operating point is achieved. Critical clearing times, one of the most important indices for transient stability, can be controlled by the proposed preventive control by generator output rescheduling and generator terminal voltage control.

However the proposed preventive control method has some drawbacks. In this work, multimachine simulation is performed by considering all loads and input power increasing at the same rate. In fact this not realistic case, they changes arbitrarily. As a future work, arbitrarily load and generation changes can be studied.

Limits of the synchronous machines and the insulation problem is the another drawbacks. The active and the reactive power supplied from the generator can not exceed these limits. Hence, by the use of preventive control the generators could be operated within their limits successfully.

Inspections show that daily load curves are almost same except the weekend and special days. These curves are used to estimate the future condition critical clearing times and rotor angles.

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APPENDIX A

LOAD FLOW

1.1 Introduction

Load flow calculations provide power flows and voltages for specified power system subject to the regulating capability of generators, condensers, and tap changing under load transformers as well as specified net interchange between individual operating systems. This information is essential for the continuous evaluation of the current performance of a power system and for analyzing the effectiveness of alternative plans for system expansion to meet increased load demand. These analyses require the calculation of numerous load flows for both normal and emergency operating conditions.

The load flow problem consists of the calculation of power flows and voltages of a network for specified terminal or bus conditions. A single-phase representation is adequate since power systems are usually balanced. Associated with each bus are four quantities: the real and reactive power, the voltage magnitude, and the phase angle. Three types of buses are represented in the load flow calculation and at a bus, two of the four quantities are specified. It is necessary to select one bus, called the slack bus, to provide the additional real and reactive power to supply the transmission losses, since these are unknown until the final solution is obtained. At this bus the voltage magnitude and the phase angle are specified. The remaining buses of the system are designated either as voltage controlled buses or load buses. The real power and voltage magnitude are specified at a voltage-controlled bus. The real and reactive powers are specified at a load bus.
Network connections are described by using code numbers assigned to each bus. These numbers specify the terminals of the transmission lines and transformers. Code numbers are used also to identify the types of buses, the location of static capacitors, shunt reactors, and those network elements in which off nominal turns ratios of transformers are to be represented.

The two primary considerations in the development of an effective engineering computer program are: (1) the formulation of a mathematical description of the problem; and (2) the application of a numerical method for a solution. The analysis of the problem must be consider the inter relation between these two factors.

The mathematical formulation of the load flow problem results in a system of algebraic nonlinear equations. These equations can be established by using the bus frame of reference. The coefficients of the equations depend on the selection of the dependent variables, i.e., voltages or currents. Thus, either the admittance or the impedance network matrices can be used. Bus admittance matrix is used for computer programs in this work.

The majority of load flow programs for large power system studies employ methods using the bus admittance matrix. This approach remains the most economical from the point of view of the computer time and memory requirements.

1.2 Power flow equations

The bus self and mutual admittances which compose the bus admittance matrix Y_{bus} is used in solving the power flow problem. The starting point in obtaining the data, which must be furnished to the computer, is the single line diagram of the system. Transmission lines are represented by their per phase nominal π equivalent circuits. For each line numerical values for the series impedance Z and the total line charging admittance Y are necessary so that the computer can determine all the elements of the NxN bus admittance matrix of which the typical element Y_{ij} is [1]

$$Y_{ij} = |Y_{ij}|\angle\theta_{ij} = |Y_{ij}|\cos\theta_{ij} + j|Y_{ij}|\sin\theta ij = G_{ij} + jB_{ij} \qquad (A.1)$$

Other essential information includes transformer ratings and impedances, shunt capacitor ratings, and transformer tap settings. In advance of each power flow study certain bus voltages and power injections must be given values.

The voltage at a typical bus i of the system is given in polar coordinates by

$$V_i = |Vi|\angle\delta_i = |V_i|(\cos\delta_i + j\sin\delta_i) \quad \text{(A.2)}$$

and the voltage at another bus j is similarly written by changing the subscript from i to j. The net current injected into the network at bus i in terms of the elements Y_{in} of Y_{bus} is given by the summation

$$I_i = Y_{i1}V_1 + Y_{i12}V_2 + \ldots + Y_{iN}V_N = \sum_{n=1}^{N} Y_{in}V_n \quad \text{(A.3)}$$

Let Pi and Qi denote the net real and reactive power entering the network at the bus i. Then the complex conjugate of the power injected at bus i is

$$P_i - jQ_i = V_i^* \sum_{n=1}^{N} Y_{in}V_n \quad \text{(A.4)}$$

Equation A.1 and A..2 is substituted in A..4 to obtain

$$P_i - jQ_i = \sum_{n=1}^{N} |Y_{in}V_i\ V_n| \angle\theta_{in} + \delta_n - \delta_i \quad \text{(A.5)}$$

Expanding this equation and equating real and reactive parts to obtain

$$P_i = \sum_{n=1}^{N} |Y_{in}V_i\ V_n| \cos(\theta_{in} + \delta_n - \delta_i) \quad \text{(A.6)}$$

$$Q_i = \sum_{n=1}^{N} \left| Y_{in} V_i \; V_n \right| \sin(\theta_{in} + \delta_n - \delta_i) \qquad (A.7)$$

Equation A.6 and A.7 constitute the polar form of the power flow equations; they provide calculated values for the net real power Pi and reactive power Qi entering the network at typical bus i. Let P_{gi} denote the scheduled power being generated at bus i and P_{di} denote the scheduled power demand of the load at that bus. Then $P_{i,sch} = P_{gi} - P_{di}$ is the net scheduled power being injected into the network at bus i. Denoting the calculated value of Pi by $P_{i,calc}$ leads to the definition of mismatch ΔPi as the scheduled value $P_{i,sch}$ minus the calculated value $P_{i,calc}$,

$$\Delta P_i = P_{i,sch} - P_{i,calc} = (P_{gi} - P_{di}) - P_{i,calc} \qquad (A.8)$$

Likewise, for reactive power at bus i we have

$$\Delta Q_i = Q_{i,sch} - Q_{i,calc} = (Q_{gi} - Q_{di}) - Q_{i,calc} \qquad (A.9)$$

Mismatches occur in the course of solving a power flow problem when calculated values of Pi and Qi do not coincide with the scheduled values. If the calculated values $P_{i,calc}$ and $Q_{i,calc}$ match the scheduled values $P_{i,sch}$ and $Q_{i,sch}$ perfectly, then it is said that the mismatches ΔPi and ΔQi are zero at bus i,, and the power balance equations are written

$$g_i' = P_i - P_{i,sch} = P_i - (P_{gi} - P_{di}) = 0 \qquad (A.10)$$

$$g_i'' = Q_i - Q_{i,sch} = Q_i - (Q_{gi} - Q_{di}) = 0 \qquad (A.11)$$

If bus i has no generation or load, the appropriate terms are set equal to zero in equation A.10 and A.11. Each bus of the network has two such equations, and the power flow problem is to solve equation A.6 and A.7 for the values of the unknown bus voltages which cause equation A.10 and A.11 to be numerically satisfied at each bus. There is no scheduled value $P_{i,sch}$ for bus i, then the mismatch $\Delta Pi = P_{i,sch} - P_{i,calc}$ cannot be defined and there is no requirement to satisfy the corresponding equation A.10 in the course of solving the power flow problem. Similarly, if $Q_{i,sch}$ is not specified at bus i, then equation A.11 does not have to be satisfied .

Four potentially unknown quantities associated with each bus i are Pi, Qi, voltage angle δi and voltage magnitude |Vi|. At most, there are two equations like equation A.10 and A.11 available for each node, and so we must consider how the number of the unknown quantities can be reduced to agree with the number of available equations before beginning to solve the power flow problem. The general practice in power flow studies is to identify three types of buses in the network. At each bus i two of the four quantities δi, |Vi|, Pi and Qi are specified and the remaining two are calculated. Specified quantities are chosen according to the following discussion:

Load buses : At each non-generator bus, called a load bus, both P_{di} and Q_{di} drawn from the system by the load are known from historical records, load forecast, or measurement. The scheduled values $P_{i,sch} = -P_{di}$ and $Q_{i,sch} = -Q_{di}$ are known and mismatches ΔPi and ΔQi can be defined . δi and |Vi| values for the bus are being determined .

Voltage-controlled buses : Any bus of the system at which the voltage magnitude is kept constant is said to be voltage controlled. At each generator bus, we may properly specify Pgi and |Vi| with Pdi is also known, we can define mismatch ΔPi. Generator reactive power Qgi cannot be known in advance and so mismatch ΔQi is not defined. Voltage angle δi is the unknown quantity to be determined and equation A.10 for Pi is the available equation. After the power flow problem is solved, Qi can be calculated from equation A.7.

Slack Bus : The voltage angle of the slack bus serves as reference for angle of all other bus voltages. The usual practice is to set $\delta_{slack} = 0^0$. Mismatch are not defined for the slack bus, because voltage magnitude $|V_1|$ is specified as the other known quantity along with $\delta_1 = 0^0$.

To understand with P1 and Q1 are not scheduled at the slack bus, consider that;

$$P_L = \sum_{n=1}^{N} P_i = \sum_{n=1}^{N} P_{gi} - \sum_{n=1}^{N} P_{di} \qquad \text{(A.12)}$$

The term P_L in this equation is evidently the total I^2R loss in the transmission lines and transformers or the network. The individual currents in the various transmission lines of the network cannot be calculated until after the voltage magnitude and angle are known at every bus of the system. Therefore, P_L is initially unknown. In the formulation of the power flow problem, we chose one bus, the slack bus, at which Pg is not scheduled. After the power flow problem has been solved, the difference (slack) between the total specified P going into the system at all the other buses and the total output P plus I^2R losses are assigned to the slack bus. For this reason, a generator bus must be selected as the slack bus.

1.3 Solution of Power Flow Equation

The unscheduled bus voltage magnitudes and angles in the input data of the power flow study are called state variables since their values, which describe the state of the system, depend on the quantities specified at all the buses. Hence, the power flow problem is to determine values for all state variables by solving an equal number of the power flow equations based on the input data specifications. If there are N_g voltage controlled buses (not counting the slack bus) in the system of N buses, there will be ($2N-N_g-2$) equations to be solved for ($2N-N_g-2$) state variables. Once the state variables have been calculated, the complied state of the system is known and all the other quantities, which depend on the state variables, can be determined. Quantities such as P_1 and Q_1 at the slack bus, Qi at each voltage controlled bus, and the power loss P_L of the system are examples of the dependent functions. [1]

The function Pi and Qi of Equations (6) and (7) are nonlinear functions of the state variables δi and | Vi |. Hence, power flow calculations usually employ iterative techniques such as the Gauss-Seidel and Newton-Raphson procedures. The Newton-Raphson method solves the polar form of the power flow equations until the ΔP and ΔQ mismatches at all buses fall within specified tolerances. The Gauss-Seidel method solves the power flow equations in rectangular coordinates until differences in bus voltages from one iteration to another are sufficiently small. Both methods are based on bus admittance equations.

1.4 The Gauss-Seidel Method

The complexity of obtaining a formal solution for power flow in a power system arises because of the differences in the type of data specified for the different kinds of buses. Although the formulation of sufficient equations to match the number of unknown state variables is not difficult, as we have seen, the closed form of the solution is not practical. Digital solutions of the power-flow problems follow an iterative process by assigning estimated values to the unknown bus voltages and by calculating a new value for each bus voltage from the estimated values at the other buses and the real and reactive power specified. A new set of values for the voltage at each bus is thus obtained and used to calculate still another set of bus voltages. Each calculation of a new set of voltages if called iteration. The iterative process is repeated until the changes at each bus are less than a specified minimum value. [1]

For a system of N buses the general equation for the calculated voltage at any bus i where P and Q are scheduled is

$$V_i^{(k)} = \frac{1}{Y_{ii}}\left[\frac{p_{i,sch} - jQ_{i,sch}}{V_i^{(k-1)*}} - \sum_{j=1}^{i-1} Y_{ij}V_j^{(k)} - \sum_{j=i+1}^{N} Y_{ij}V_j^{(k-1)}\right] \qquad (A.13)$$

The superscript (k) denotes the number of the iteration in which the voltage is currently being calculated and (k-1) indicates the number of the preceding iteration. Thus, it is seen that the values for the voltages on the right- hand side of this equation are most recently calculated values for the corresponding buses (or the estimated voltage if k is 1 and no iteration has yet been made at that particular bus).

Convergence upon an erroneous solution is usually avoided if the initial values are of reasonable magnitude and do not differ too widely in phase. It is common practice to set the initial estimates of the unknown voltages at all load buses equal to $1.0\angle 0^0$ per unit. Such initialization is called a flat start because of the uniform voltage profile assumed.

Since equation A.13 applies only at load buses where real and reactive powers are specified, an additional step is necessary at voltage-controlled buses where voltage magnitude is to remain constant.

When voltage magnitude rather than reactive power is specified at bus i, the real and imaginary components of the voltage for each iteration are found by first computing a value for the reactive power

$$Q_i = -\mathrm{Im}\left\{ V_i^* \sum_{n=1}^{N} Y_{in} V_n \right\} \quad \text{(A.14)}$$

which has the equivalent algorithmic expression

$$Q_i^{(k)} = -\mathrm{Im}\left\{ V_i^{(k-1)*} \left[\sum_{j=1}^{i-1} Y_{ij} V_j^{(k)} - \sum_{j=i+1}^{N} Y_{ij} V_j^{(k-1)} \right] \right\} \quad \text{(A.15)}$$

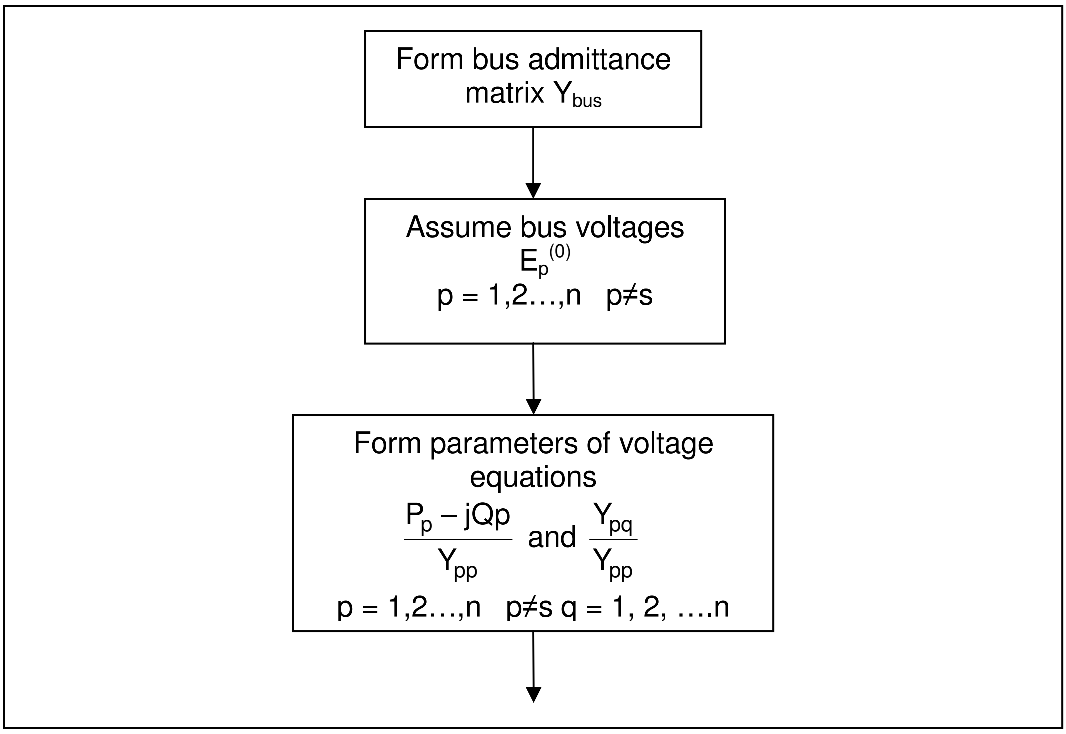
where Im means “imaginary part of” and the superscripts indicate the relevant iteration. Reactive power $Q_i^{(k)}$ is evaluated by equation A.15 for the best previous voltage values at the buses, and this value of $Q_i^{(k)}$ is substitute in equation A.13 to find a new value of $V_i^{(k)}$. The components of the new $V_i^{(k)}$ are then multiplied by the ratio of the specified constant magnitude $|V_i|$ to the magnitude of $V_i^{(k)}$ found by equation A.13. The result is the corrected complex voltage of the specified magnitude.

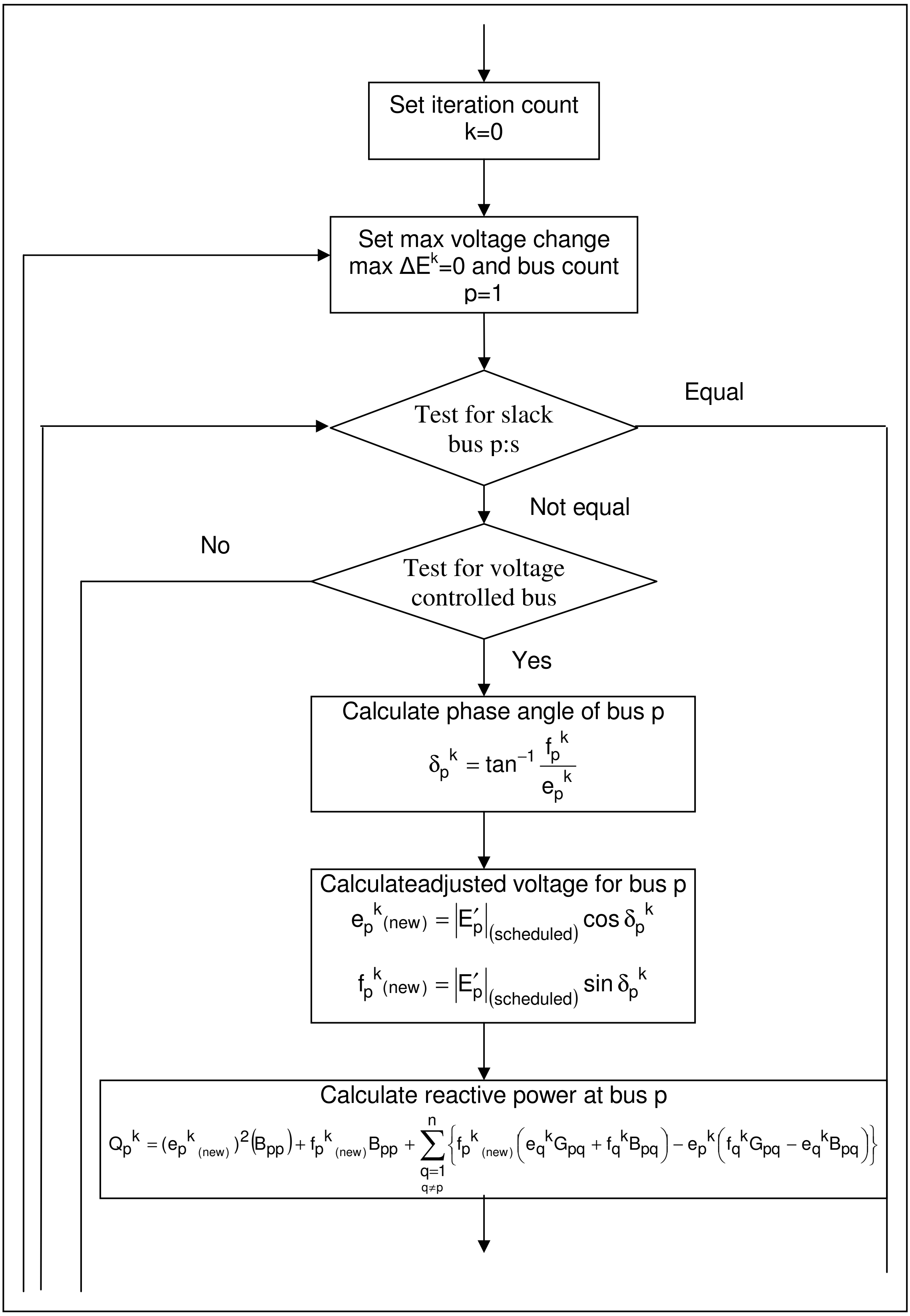
Experience with the Gausse-Seidel method of solution of power-flow problems has shown that the number of iterations required may be reduced considerably if the correction in voltage at each bus is multiplied by some constant that increases the amount of correction to bring the voltage closer to the value it is approaching. The multiplier that accomplishes this improved convergence is called an acceleration factor. The difference between the newly calculated voltage and the best previous voltage at the bus is multiplied by the appropriate acceleration factor to obtain a better correction to be added to the previous value. More generally, for the bus i during iteration k the accelerated value is given by

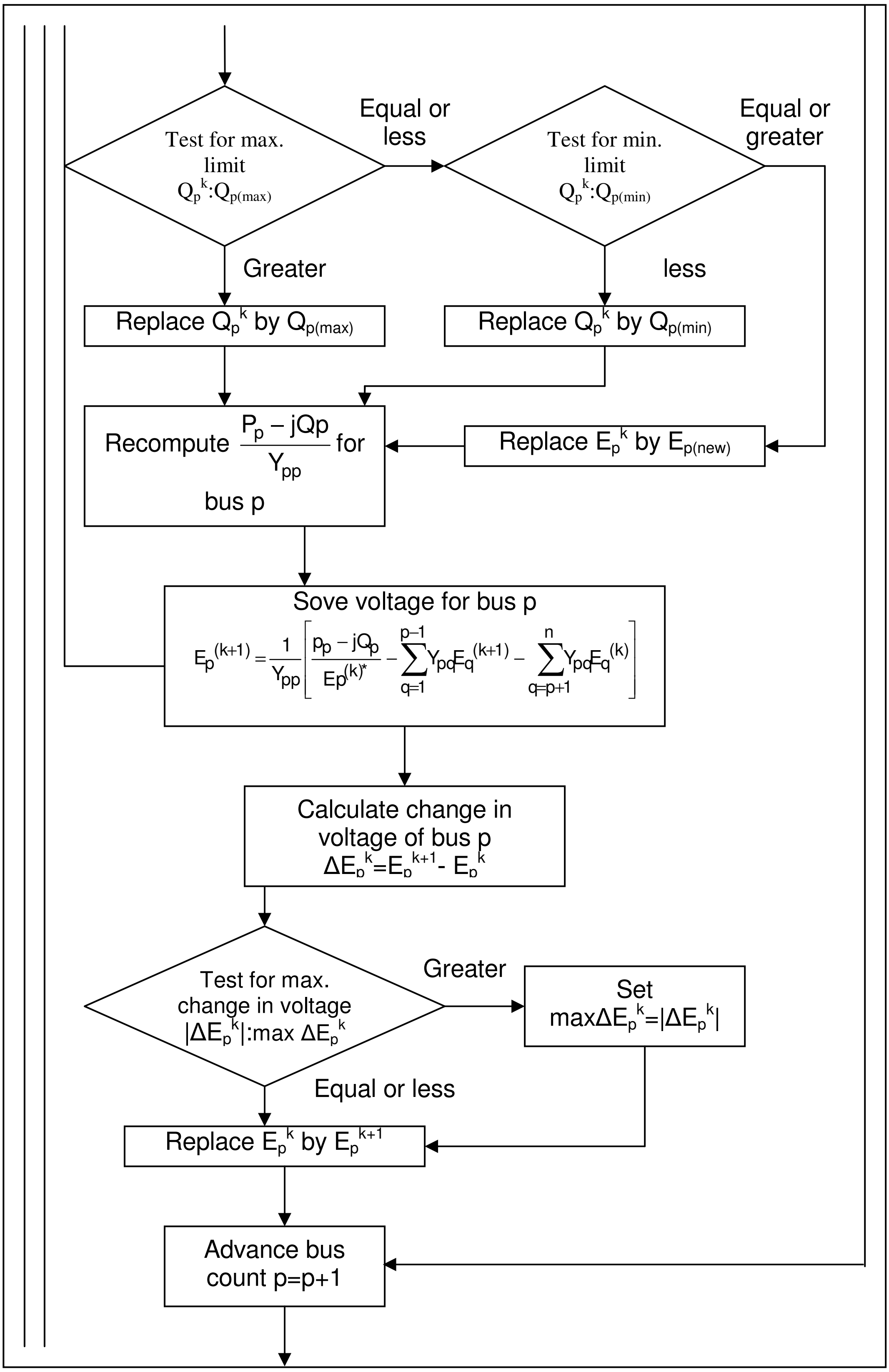
$$V_i^{(k)}{}_{,acc} = (1-\alpha)V_i^{(k-1)}{}_{,acc} + \alpha V_i^{(k)} = V_i^{(k-1)}{}_{,acc} + \alpha\left(V_i^{(k)} - V_i^{(k-1)}{}_{,acc}\right) \quad \text{A.16}$$

In this equation α is the acceleration factor. If α=1, then the Gausse-Seidel computed value of V_i is stored as the current value. In power-flow studies α is generally set at about 1.6 and cannot exceed 2 if convergence is to occur.

The sequence of steps for the load flow solution by the Gauss-Seidel iterative method is shown in Figure A.1. In this flow chart voltage of the bus shown by E




Set iteration count
k=0
Set max voltage change
max ΔE^k=0 and bus count
p=1
Test for slack
bus p:s
Equal
Not equal
No
Test for voltage
controlled bus
Yes
Calculate phase angle of bus p
$\delta_p^k = \tan^{-1}\frac{f_p^k}{e_p^k}$
Calculateadjusted voltage for bus p
$e_p^k{}_{(new)} = |E'_p|_{(scheduled)} \cos\delta_p^k$
$f_p^k{}_{(new)} = |E'_p|_{(scheduled)} \sin\delta_p^k$
Calculate reactive power at bus p
$Q_p^k = (e_p^k{}_{(new)})^2(B_{pp}) + f_p^k{}_{(new)}B_{pp} + \sum_{\substack{q=1\\q\neq p}}^{n}\left\{f_p^k{}_{(new)}\left(e_q^kG_{pq} + f_q^kB_{pq}\right) - e_p^k\left(f_q^kG_{pq} - e_q^kB_{pq}\right)\right\}$



Test for max. limit $Q_p^k : Q_{p(max)}$
Equal or less
Test for min. limit $Q_p^k : Q_{p(min)}$
Equal or greater
Greater
less
Replace Q_p^k by $Q_{p(max)}$
Replace Q_p^k by $Q_{p(min)}$
Recompute $\frac{P_p - jQp}{Y_{pp}}$ for bus p
Replace E_p^k by $E_{p(new)}$
Sove voltage for bus p
$E_p^{(k+1)} = \frac{1}{Y_{pp}}\left[\frac{P_p - jQ_p}{Ep^{(k)*}} - \sum_{q=1}^{p-1} Y_{pq}E_q^{(k+1)} - \sum_{q=p+1}^{n} Y_{pq}E_q^{(k)}\right]$
Calculate change in voltage of bus p
$\Delta E_p^k = E_p^{k+1} - E_p^k$
Test for max. change in voltage $|\Delta E_p^k| : \max \Delta E_p^k$
Greater
Set $\max \Delta E_p^k = |\Delta E_p^k|$
Equal or less
Replace E_p^k by E_p^{k+1}
Advance bus count p=p+1

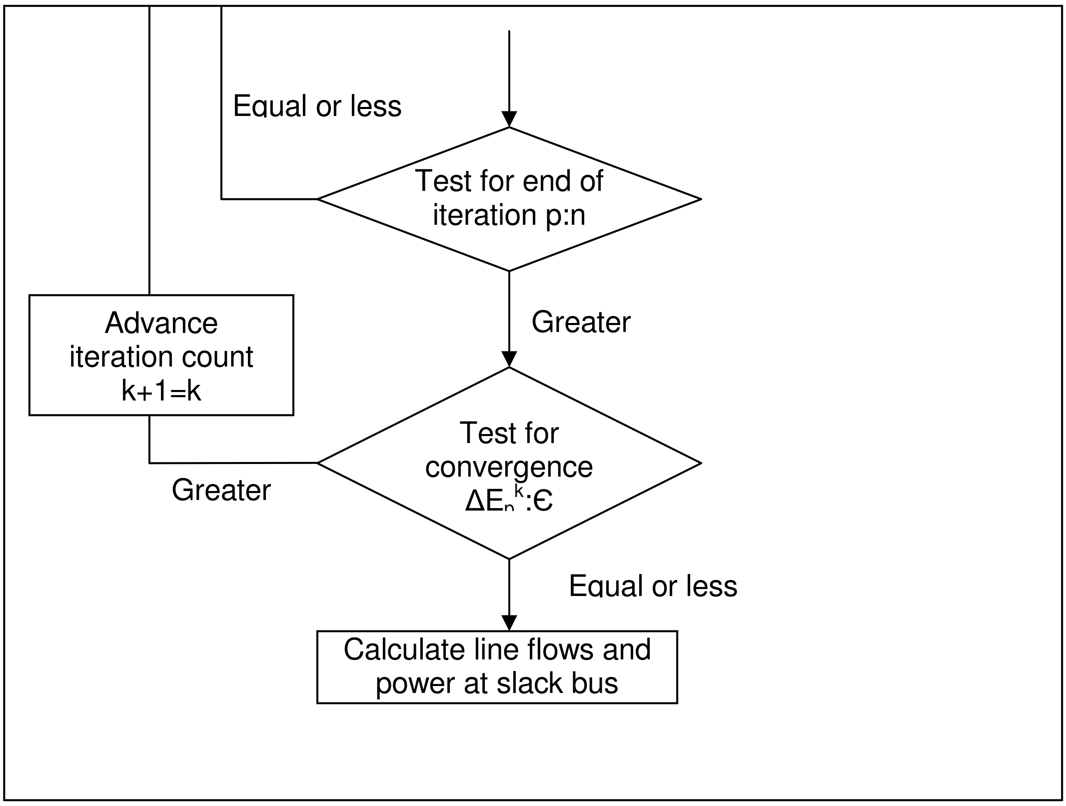


Figure A.1 Load flow solution by the Gauss-Seidel iterative method using Y_{BUS}

1.5 The Newton-Raphson Method Power-Flow Solution

The load-flow problem can be solved by the Newton-Raphson method using a set of nonlinear equations to express the specified real and reactive powers in terms of bus voltages. The power at bus p is [2]

$$P_p - jQ_p = E_p^* I_p \tag{A.17}$$

Substituting from the network performance equation $I_{BUS} = Y_{BUS} E_{BUS}$ for I_p in equation A.17.

$$P_p - jQ_p = E_p^* \sum_{q=1}^{n} Y_{pq} E_q \tag{A.18}$$

Since $E_p = e_p + jf_p$ and $Y_{pq} = G_{pq} - j\,B_{pq}$, equation A.18 becomes

$$P_p = \sum_{q=1}^{n} \left\{ e_p \left(e_q G_{pq} + f_q B_{pq} \right) + f_p \left(f_q G_{pq} - e_q B_{pq} \right) \right\} \qquad \text{(A.19)}$$

$$Q_p = \sum_{q=1}^{n} \left\{ f_p \left(e_q G_{pq} + f_q B_{pq} \right) - e_p \left(f_q G_{pq} - e_q B_{pq} \right) \right\} \qquad \text{(A.20)}$$

This formulation results in a set of nonlinear simultaneous equations, two for each bus of the system. The real and reactive powers P_p and Q_p are known and the real and imaginary components of voltage e_p and f_p are unknown for all buses except the slack bus, where the voltage is specified and remains fixed. Thus there are 2(n-1) equations to be solved for a load flow solution.

The Newton-Raphson method requires that a set of linear equations to be formed expressing the relationship between the changes in real and reactive powers and the components of bus voltages as follows:

$$\begin{bmatrix} \Delta P_1 \\ \cdots \\ \Delta P_{n-1} \\ \hline \Delta Q_1 \\ \cdots \\ \Delta Q_{n-1} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_1}{\partial e_1} & \cdots & \frac{\partial P_1}{\partial e_{n-1}} & \frac{\partial P_1}{\partial f_1} & \cdots & \frac{\partial P_1}{\partial f_{n-1}} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{\partial P_{n-1}}{\partial e_1} & \cdots & \frac{\partial P_{n-1}}{\partial e_{n-1}} & \frac{\partial P_{n-1}}{\partial f_1} & \cdots & \frac{\partial P_{n-1}}{\partial f_{n-1}} \\ \hline \frac{\partial Q_1}{\partial e_1} & \cdots & \frac{\partial Q_1}{\partial e_{n-1}} & \frac{\partial Q_1}{\partial f_1} & \cdots & \frac{\partial Q_1}{\partial f_{n-1}} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{\partial Q_{n-1}}{\partial e_1} & \cdots & \frac{\partial Q_{n-1}}{\partial e_{n-1}} & \frac{\partial Q_{n-1}}{\partial f_1} & \cdots & \frac{\partial Q_{n-1}}{\partial f_{n-1}} \end{array} \right] \begin{bmatrix} \Delta e_1 \\ \cdots \\ \Delta e_{n-1} \\ \hline \Delta f_1 \\ \cdots \\ \Delta f_{n-1} \end{bmatrix} \qquad \text{(A.21)}$$

where the coefficient matrix is the Jacobian and the nth bus is the slack. In matrix form, equation A.21 is

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta e \\ \Delta f \end{bmatrix} \quad \text{(A.22)}$$

Equation for determining the elements of the Jacobian can be derived from the bus power equations. The real power from the equation A.19 is

$$P_p = e_p\left(e_pG_{pp} + f_pB_{pp}\right) + f_p\left(f_pG_{pp} + e_pB_{pp}\right) + \sum_{\substack{q=1 \\ q\neq p}}^{n}\left\{e_p\left(e_qG_{pq} + f_qB_{pq}\right) + f_p\left(f_qG_{pq} - e_qB_{pq}\right)\right\}$$

p= 1, 2, 3, … ,n-1 (A.23)

Differentiating, the off-diagonal elements of J_1 are

$$\frac{\partial P_p}{\partial e_q} = e_pG_{pq} - f_pB_{pq} \qquad q \neq p \quad \text{(A.24)}$$

and the diagonal elements of J_1 are

$$\frac{\partial P_p}{\partial e_q} = 2e_pG_{pp} - f_pB_{pq} - f_pB_{pp} + \sum_{\substack{q=1 \\ q\neq p}}^{n}\left(e_qG_{pq} + f_qB_{pq}\right) \quad \text{(A.25)}$$

However, the equation for the current at bus p is

$$I_p = c_p + jd_p = \left(G_{pp} - jB_{pp}\right)\left(e_p + jf_p\right) + \sum_{\substack{q=1 \\ q\neq p}}^{n}\left(G_{pq} + jB_{pq}\right)\left(e_q + jf_q\right) \quad \text{(A.26)}$$

which can be separated into the real and imaginary parts

$$c_p = e_pG_{pp} - f_pB_{pq} + \sum_{\substack{q=1 \\ q\neq p}}^{n}\left(e_qG_{pq} + f_qB_{pq}\right)$$

$$d_p = f_p G_{pp} - e_p B_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} \left(f_q G_{pq} + e_q B_{pq} \right) \quad p = 1, 2, 3, \ldots, n\text{-}1 \tag{A.27}$$

Therefore, the expression for the diagonal elements of J_1 can be simplified by substituting the real component of current c_p in equation A.25. to obtain

$$\frac{\partial P_p}{\partial e_q} = e_p G_{pp} - f_p B_{pp} + c_p \tag{A.28}$$

From equation A.23, the off- diagonal elements of J_2 are

$$\frac{\partial P_p}{\partial f_q} = e_p B_{pq} + f_p G_{pq} \qquad q \neq p \tag{A.29}$$

and the diagonal element of J_2 are

$$\frac{\partial P_p}{\partial f_q} = e_p B_{pp} + 2 f_p G_{pq} - e_p B_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} \left(f_q G_{pq} - e_q B_{pq} \right) \tag{A.30}$$

The imaginary component of current from equation A.27 is substitute in A.30 to obtain

$$\frac{\partial P_p}{\partial f_q} = e_p B_{pp} + f_p G_{pp} + d_p \tag{A.31}$$

The reactive power from equation A.20 is

$$Q_p = f_p \left(e_p G_{pp} + f_p B_{pp} \right) - e_p \left(f_p G_{pp} - e_p B_{pp} \right) + \sum_{\substack{q=1 \\ q \neq p}}^{n} \left\{ f_p \left(e_q G_{pq} + f_q B_{pq} \right) - e_p \left(f_q G_{pq} - e_q B_{pq} \right) \right\}$$

$p = 1, 2, 3, \ldots, n\text{-}1$ (A.32)

Differentiating, the off- diagonal elements of J_3 are

$$\frac{\partial Q_p}{\partial e_q} = e_p B_{pq} + f_p G_{pq} \qquad q \neq p \tag{A.33}$$

and the diagonal elements of J_3 are

$$\frac{\partial Q_p}{\partial e_p} = f_p G_{pp} - 2f_p G_{pp} + 2e_p B_{pp} - \sum_{\substack{q=1 \\ q \neq p}}^{n} \left(f_q G_{pq} - e_q B_{pq} \right) \tag{A.34}$$

The imaginary component of current from equation A.27 is substituted in equation A.34 to obtain

$$\frac{\partial Q_p}{\partial e_p} = e_p B_{pq} + f_p G_{pq} - d_q \tag{A.35}$$

From equation A.32, the off-diagonal elements of J_4 are

$$\frac{\partial Q_p}{\partial f_q} = -e_p G_{pq} + f_p B_{pq} \qquad q \neq p \tag{A.36}$$

and the diagonal element of J_4 are

$$\frac{\partial Q_p}{\partial f_p} = e_p G_{pp} + 2f_p B_{pp} - e_p G_{pp} + \sum_{\substack{q=1 \\ q \neq p}}^{n} \left(e_q G_{pq} + f_q B_{pq} \right) \tag{A.37}$$

The real component of current from equation A.27 is substituted in equation A.37 to obtain

$$\frac{\partial Q_p}{\partial f_p} = -e_p G_{pp} + f_p B_{pp} + c_p \tag{A.38}$$

Given an initial set of bus voltages, the real and the reactive powers are calculated from equations A.19 and A.20. The changes in power are the differences between the scheduled and calculated values

$$\Delta P_p^{\,k} = P_{p(scheduled)} - P_p^{\,k}$$

$$\Delta Q_p^{\,k} = Q_{p(scheduled)} - Q_p^{\,k} \qquad p = 1, 2, 3, \ldots, n\text{-}1 \qquad \text{(A.39)}$$

The estimated bus voltages and calculated powers are used to compute bus currents in order to evaluate the elements of the Jacobian. The linear set of equations A.21 can be solved for Δe_p and Δf_p, p=1, 2, 3, . . . , n-1, by a direct or an iterative method. Then, the new estimates for bus voltages are

$$e_p^{\,k+1} = e_p^{\,k} + \Delta e_p^{\,k}$$

$$f_p^{\,k+1} = f_p^{\,k} + \Delta f_p^{\,k} \qquad \text{(A.40)}$$

The process is repeated until ΔP_p^k and ΔQ_p^k for all buses are within a specified tolerance.

1.5.1 Voltage Control Buses

The equations for a voltage controlled bus p are [2]

$$P_p = \sum_{q=1}^{n} \left\{ e_p \left(e_q G_{pq} + f_q B_{pq} \right) + f_p \left(f_q G_{pq} - e_q B_{pq} \right) \right\} \qquad \text{(A.41)}$$

and

$$\left| E_p^{\,2} \right| = e_p^{\,2} + f_p^{\,2} \qquad \text{(A.42)}$$

where equation A.42 replace the equation for the reactive power. The matrix equation relating the changes in bus powers and the square of voltage magnitudes to changes in real and imaginary components of voltage is

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \hdashline \Delta |E|^2 \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \\ \hdashline J_5 & J_6 \end{bmatrix} \begin{bmatrix} \Delta e \\ \Delta f \end{bmatrix} \qquad \text{(A.43)}$$

The elements of the sub matrices J_1, J_2, J_3 and J_4 are calculated as shown before. The off-diagonal elements of J_5, from equation A.42, are

$$\frac{\partial |E_p|^2}{\partial e_q} = 0 \qquad q \neq p \qquad \text{(A.44)}$$

and the diagonal elements are

$$\frac{\partial |E_p|^2}{\partial e_p} = 2e_p \qquad \text{(A.45)}$$

Similarly, the off-diagonal elements of J_6 are

$$\frac{\partial |E_p|^2}{\partial f_q} = 0 \qquad q \neq p \qquad \text{(A.46)}$$

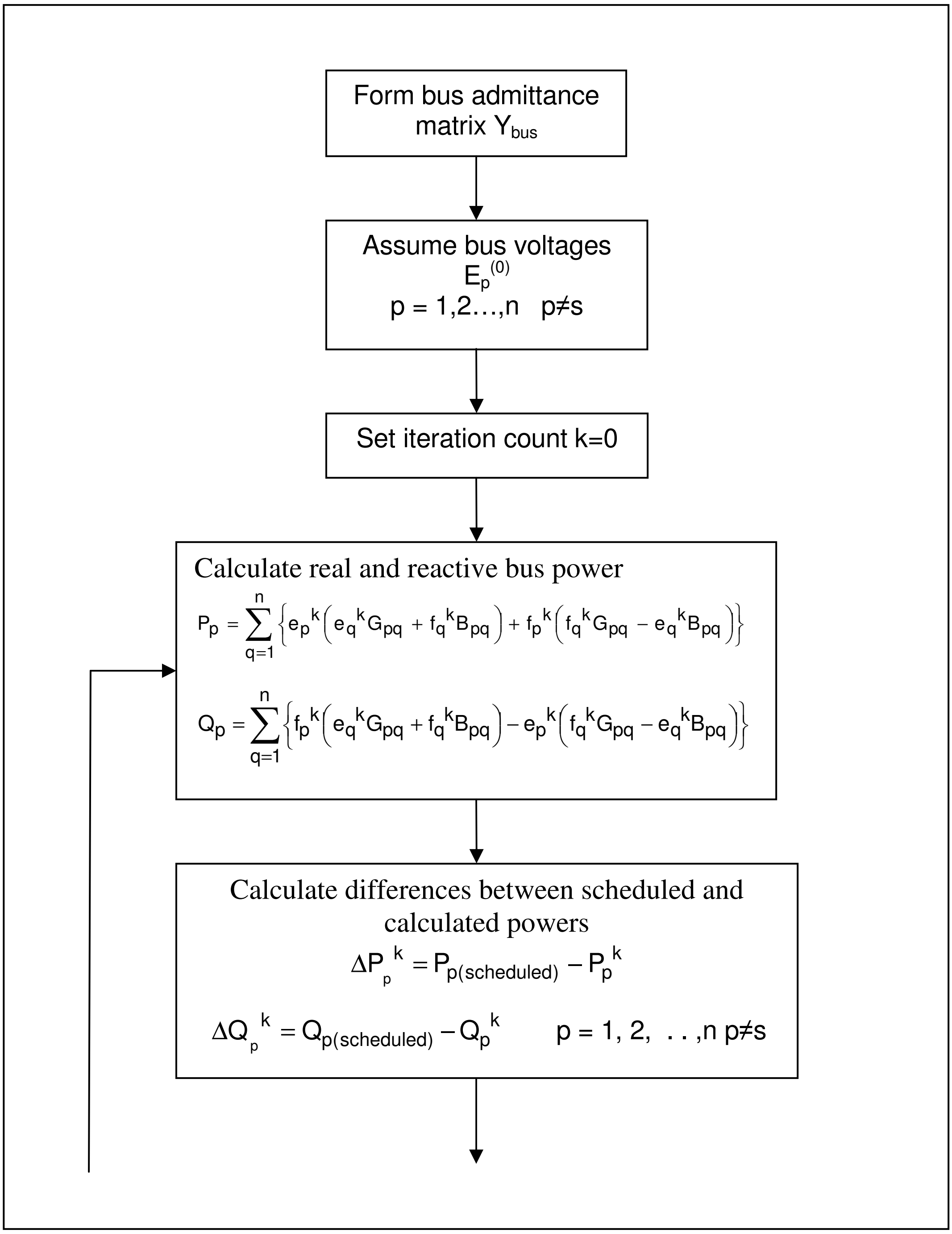
and the diagonal elements are

$$\frac{\partial |E_p|^2}{\partial f_p} = 2f_p \qquad \text{(A.47)}$$

The change in the squire of the voltage magnitude at bus p is

$$\Delta |E_p{}^k|^2 = \left\{ |E_p|_{p(scheduled)} \right\}^2 - |E_p{}^k|^2 \qquad \text{(A.48)}$$

If sufficient reactive capability is not available to hold the desired magnitude of bus voltage the reactive power must be fixed at a limit. In this case the bus is treated as a load bus with fixed reactive power. The sequence of steps for the load flow solution by the Newton-Raphson method is shown in Figure A.2.



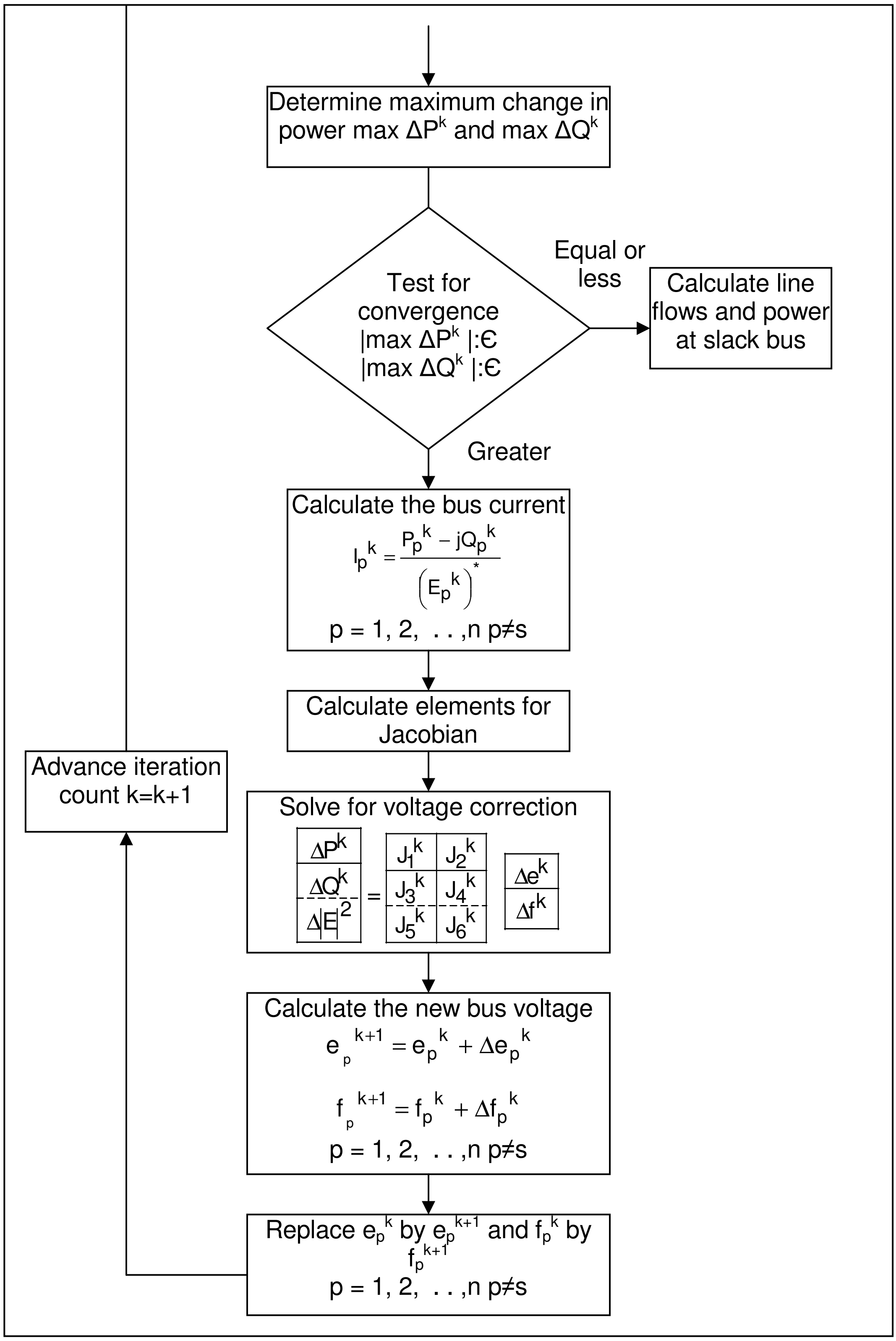


Figure A.2. Load-flow solution by the Newton-Raphson method using Ybus.

1.6 Application For Load Flow

1.6.1 IEEE 14 Bus System

IEEE 14 bus system data and load flow results are shown below. The computer program designed for this thesis is tested by this system. Gauss-Seidel method is used in this application and the result shown in Table A.6 is taken. The results are very close to the test system.

Table A.1 Bus data and load flow result

Bus No	Bus Voltage		Generation		Load	
	Magnitude per unit	Phase angle degrees	Real MW	Reactive MVAR	Real MW	Reactive MVAR
1	1.060	0.0	232.4	-16.9	0.0	0.0
2	1.045	-4.98	40	42.4	21.7	12.7
3	1.010	-12.72	0.0	23.4	94.2	19.0
4	1.019	-10.33	0.0	0.0	47.8	3.9
5	1.020	-8.78	0.0	0.0	7.6	1.6
6	1.070	-14.22	0.0	12.2	11.2	7.5
7	1.062	-13.37	0.0	0.0	0.0	0.0
8	1.090	-13.36	0.0	17.4	0.0	0.0
9	1.056	-14.94	0.0	0.0	29.5	16.6
10	1.051	-15.10	0.0	0.0	9.0	5.8
11	1.057	-14.79	0.0	0.0	3.5	1.8
12	1.055	-18.07	0.0	0.0	6.1	1.6
13	1.050	-15.16	0.0	0.0	13.5	5.8
14	1.036	-16.04	0.0	0.0	14.9	5.0

Table A.2 Line data

Line No	Between Buses	Line Impedance		Half line charging susceptance per unit
		R per unit	X per unit	
1	1-2	0,01938	0,05917	0,02640
2	2-3	0,04699	0,19797	0,02190
3	2-4	0,05811	0,17632	0,01870
4	1-5	0,05403	0,22304	0,02460
5	2-5	0,05695	0,17388	0,01700
6	3-4	0,06701	0,17103	0,01730
7	4-5	0,01335	0,04211	0,0064
8	5-6	0,0	0,25202	0,0
9	4-7	0,0	0,20912	0,0
10	7-8	0,0	0,17615	0,0
11	4-9	0,0	0,55618	0,0
12	7-9	0,0	0,11001	0,0
13	9-10	0,03181	0,08450	0,0
14	6-11	0,09498	0,19890	0,0
15	6-12	0,12291	0,25581	0,0
16	6-13	0,06615	0,13027	0,0
17	9-14	0,12711	0,27038	0,0
18	10-11	0,08205	0,19207	0,0
19	12-13	0,22092	0,19988	0,0
20	13-14	0,17093	0,34802	0,0

Table A.3 Transformer data

Transformer	Between Buses	Tap setting
1	4-7	0,978
2	4-9	0,969
3	5-6	0,932

Table A.4 Shunt capacitor data

Bus Number	Susceptance per unit
1	0,978

Table A.5 Regulated bus data

Bus No	Voltage magnitude per unit	Reactive Power Limits	
		Minimum MVAR	Maximum MVAR
2	1.045	-40.0	50.0
3	1.010	0.0	40.0
6	1.070	-6.0	24.0
8	1.090	-6.0	24.0

Table A.6 Computer program results

Form14

Iteration Count	Bus No	Bus Voltages Real Part	Bus Voltages Imaginary Part	Bus Voltages Magnitude	Bus Voltages Angle(deg)
96	14	0,994728	-0,285627	1,050243	-15,15096
97	1	1,060000	0,000000	1,034923	-16,02093
97	2	1,041047	-0,090810	1,060000	0,00000
97	3	0,985137	-0,222723	1,045000	-4,98524
97	4	0,999161	-0,181282	1,010000	-12,73944
97	5	1,006444	-0,155084	1,015473	-10,28357
97	6	1,037223	-0,262809	1,018322	-8,75986
97	7	1,031922	-0,244652	1,070000	-14,21823
97	8	1,060600	-0,251451	1,060527	-13,33764
97	9	1,019422	-0,271597	1,090000	-13,33763
97	10	1,014033	-0,273228	1,054982	-14,91835
97	11	1,021548	-0,269523	1,050198	-15,08002
97	12	1,018818	-0,274371	1,056505	-14,77999
97	13	1,013737	-0,274495	1,055116	-15,07236
97	14	0,994728	-0,285627	1,050243	-15,15096
98	1	1,060000	0,000000	1,034923	-16,02093
98	2	1,041047	-0,090810	1,060000	0,00000
98	3	0,985137	-0,222723	1,045000	-4,98524
98	4	0,999161	-0,181282	1,010000	-12,73944
98	5	1,006444	-0,155084	1,015473	-10,28357
98	6	1,037223	-0,262809	1,018322	-8,75986
98	7	1,031922	-0,244652	1,070000	-14,21823
98	8	1,060600	-0,251451	1,060527	-13,33764
98	9	1,019422	-0,271597	1,090000	-13,33763
98	10	1,014033	-0,273228	1,054982	-14,91835
98	11	1,021548	-0,269523	1,050198	-15,08002
98	12	1,018818	-0,274371	1,056505	-14,77999
98	13	1,013737	-0,274495	1,055116	-15,07236
98	14	0,994728	-0,285627	1,050243	-15,15096
				1,034923	-16,02093

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APPENDIX B

JACOBIAN MATRIX

Generator outputs are calculated by using Jacobian matrix. The following equation is used for this purpose:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|E| \end{bmatrix} \quad (B.1)$$

The Jacobian matrix elements can be obtained by using the polar coordinates as follow: The polar form of bus voltage and bus admittance at bus p and between bus p and q respectively are

$$E_p = |E_p| e^{j\delta p} \quad (B.2)$$

$$Y_{pq} = |Y_{pq}| e^{-j\theta pq} \quad (B.3)$$

anp power at bus p is

$$P_p - jQ_p = E_p^{*} \sum_{q=1}^{n} Y_{pq} E_q \quad (B.4)$$

Substituting equation B.2 and B.3 into the equation B.4,

$$P_p - jQ_p = \sum_{q=1}^{n} |E_p E_q Y_{pq}| e^{-j(\theta pq + \delta p - \delta q)} \quad (B.5)$$

Since,

$$e^{-j(\theta pq+\delta p-\delta q)} = \cos(\theta_{pq} + \delta_p - \delta_q) - j\sin(\theta_{pq} + \delta_p - \delta_q) \quad \text{(B.6)}$$

The real and the imaginary of the components of the power are

$$P_p = \sum_{q=1}^{n} \left|E_p E_q Y_{pq}\right| \cos(\theta_{pq} + \delta_p - \delta_q) \quad \text{(B.7)}$$

$$Q_p = \sum_{q=1}^{n} \left|E_p E_q Y_{pq}\right| \sin(\theta_{pq} + \delta_p - \delta_q) \quad p=1, 2, 3, \ldots, n-1 \quad \text{(B.8)}$$

The elements of the Jacobian are calculated from equations B.7 and B.8

For J_1, the off-diagonal elements

$$\frac{\partial P_p}{\partial \delta_q} = \left|E_p E_q Y_{pq}\right| \sin(\theta_{pq} + \delta_p - \delta_q) \quad q \neq p \quad \text{(B.9)}$$

The diagonal elements

$$\frac{\partial P_p}{\partial \delta_p} = -\sum_{\substack{q=1 \\ q \neq p}}^{n} \left|E_p E_q Y_{pq}\right| \sin(\theta_{pq} + \delta_p - \delta_q) \quad \text{(B.10)}$$

For J_2, the off-diagonal elements

$$\frac{\partial P_p}{\partial \left|E_q\right|} = \left|E_p Y_{pq}\right| \cos(\theta_{pq} + \delta_p - \delta_q) \quad q \neq p \quad \text{(B.11)}$$

The diagonal elements

$$\frac{\partial P_p}{\partial \left|E_p\right|} = 2\left|E_p Y_{pp}\right| \cos(\theta_{pp}) + \sum_{\substack{q=1 \\ q \neq p}}^{n} \left|E_q Y_{pq}\right| \cos(\theta_{pq} + \delta_p - \delta_q) \quad \text{(B.12)}$$

For J_3, the off-diagonal elements

$$\frac{\partial Q_p}{\partial \delta_q} = -\left|E_p E_q Y_{pq}\right| \cos(\theta_{pq} + \delta_p - \delta_q) \quad q \neq p \tag{B.13}$$

The diagonal elements

$$\frac{\partial Q_p}{\partial \delta_p} = \sum_{\substack{q=1 \\ q \neq p}}^{n} \left|E_p E_q Y_{pq}\right| \cos(\theta_{pq} + \delta_p - \delta_q) \tag{B.14}$$

For J_4, the off-diagonal elements

$$\frac{\partial P_p}{\partial \left|E_q\right|} = \left|E_p Y_{pq}\right| \sin(\theta_{pq} + \delta_p - \delta_q) \qquad q \neq p \tag{B.15}$$

The diagonal elements

$$\frac{\partial Q_p}{\partial \left|E_p\right|} = 2\left|E_p Y_{pp}\right| \sin(\theta_{pp}) + \sum_{\substack{q=1 \\ q \neq p}}^{n} \left|E_q Y_{pq}\right| \sin(\theta_{pq} + \delta_p - \delta_q) \tag{B.16}$$

APPENDIX C

GENERATOR OUTPUT RESCHEDULING AND GENERATOR TERMINAL VOLTAGE CONTROL

Power system is very large and includes a lot of machines, buses in it. Therefore, one of the generator operations doesn't have much of an effect on the power system. When a generator operates in parallel with a large system, the frequency and the terminal voltage of all the machines must be the same. If its governor set point increased, the no-load frequency of the generator shifts upward. Since the frequency of the system is unchanged, the power supplied by the generator is increases. Notice in the phasor diagram Figure C.1 that $E_A.\sin\delta$ (V_Φ is constant) has increased, while the magnitude of E_A (=K.Φ.ω) remains constant, since both the field current I_F and the speed of the rotation ω are unchanged. In section 3.5 active power value is determined and it can be adjusted by governor system. As the governor set points are further increased, the no-load frequency increases and the power supplied by the generator increases. E_A remains at constant magnitude while $E_A.\sin\delta$ is further increased by changing rotor angle δ.

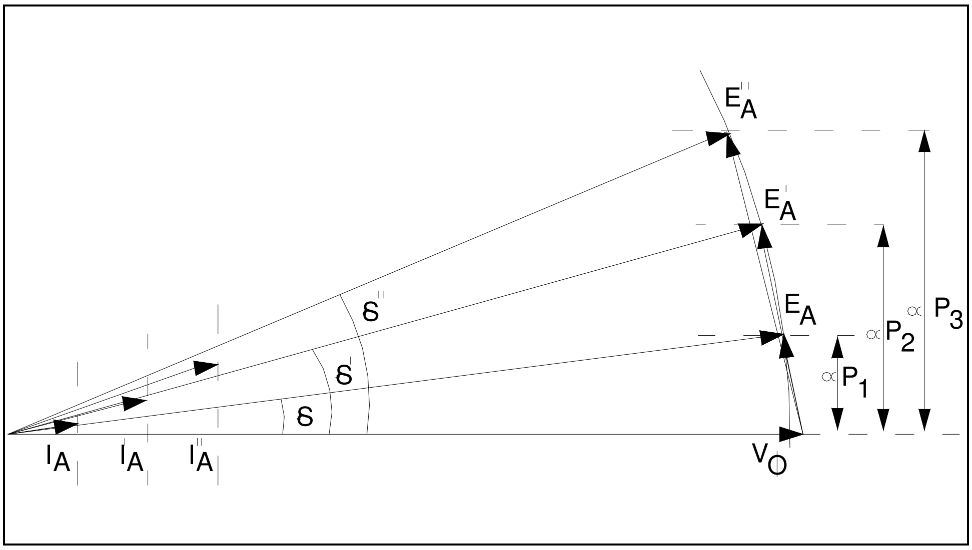

Figure C.1 The effects of increasing the governor's set point on the phasor diagram

If the power supplied is constant as the field current is changed, then the distance proportional to the power in the phasor diagram (I_A.cosθ and E_A.sinδ) can not change. When the field current is increased, the flux Φ increases and therefore E_A=K.Φ.ω increases. If E_A increase, but E_A.sinδ must remain constant, then the phasor E_A must "slide" along the line of constant power, as shown in Figure C.2. Since V_Φ is constant, the angle of jXs.I_A changes as shown, and therefore the angle and magnitude of I_A change. As a result the distance proportional to Q (I_A.sinθ) increases.

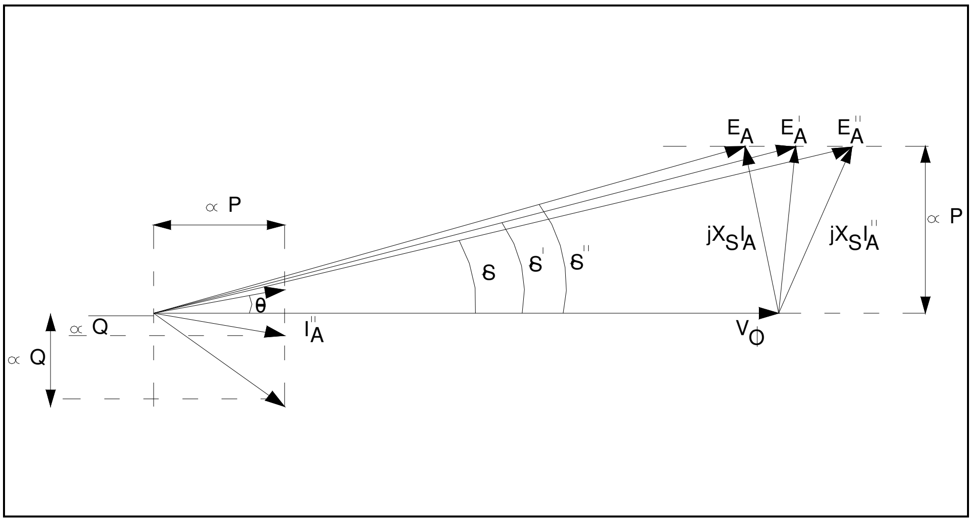

Figure C.2 The effects of increasing the generator's field current on the phasor diagram

Desired rotor angles δ_{pd} are adjusted by satisfying the determined active and reactive powers which are determined in section 3.5.