POWER SYSTEM STABILITY IMPROVEMENT THROUGH A COORDINATED QUASI-OPTIMAL CONTROL STRATEGY

BY

MD. ZIAUL KARIM

A THESIS

SUBMITTED TO THE DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE IN ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY, DHAKA

AUGUST, 1988.

The thesis titled, "Power System Stability Improvement Through A Coordinated Quasi-Optimal Control Strategy", submitted by Md. Ziaul Karim Roll No. 861338P, Registration No. 80053 of M.Sc. Engg.(EEE) has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Engineering (Electrical and Electronic).

BOARD OF EXAMINERS

1. (Dr. Md. Mujibur Rahman)
Professor and Head,
Department of Electrical and Electronic
Engineering, BUET, Dhaka.
— Chairman (Supervisor)

2. 17/8/88
(Dr. Enamul Basher)
Associate Professor,
Department of Electrical and Electronic
Engineering, BUET, Dhaka.
— Member

3. 17/8/88
(Dr. Taifur Ahmed Chowdhury)
Assistant Professor,
Department of Electrical and Electronic
Engineering, BUET, Dhaka.
— Member

4. (Dr. A. M. Zahoorul Huq) 17/8/88
391 Baitul Aman Housing Estate
Road No. 6, Shaymoli,
Dhaka-7.
— Member (External)

CERTIFICATE

Certified that this work was done by me and it has not been submitted elsewhere for the award of any degree or diploma.

(Dr. Md. Mujibur Rahman)
Supervisor

(Md. Ziaul Karim)
Student

ACKNOWLEDGEMENT

The author expresses his deep sense of gratitude and profound respect to his supervisor, Dr. Md. Mujibur Rahman, Professor and Head, Department of Electrical and Electronic Engineering, BUET for his continuous encouragement, constant guidance and keen supervision throughout the progress of the work.

The author also acknowledge his thanks and gratitude to Dr. Enamul Basher,Associate Professor and Dr. Taifur Ahmed Chowdhury, Assistant Professor, Department of Electrical and Electronic Engineering,BUET, for their suggestions and encouragement.

The author is especially indepted to Mr. D.A.H. Alamgir, Lecturer, Department of Electrical and Electronic Engineering, BUET, for his all possible help, fruitful advice, suggestions, discussions and guidance throughout the course of this work.Without the interest and cooperation of Mr. Alamgir, this work would almost have been impossible.

Acknowledgement is due to the Computer Center and the Department of Electrical and Electronic Engineering,BUET for providing the excellent facilities for this work.

The author also acknowledge his indeptedness and respect to his father and mother for their loving attention.

Finally, amongst his colleagues, the author is thankful to Rafiqul Morshed, Mashiur Rahman Bhuiyan and Mahmudur Rahman for their encouragement and help.

ABSTRACT

A coordinated quasi-optimal minimum-time control strategy involving dynamic-braking-resistor-shunt-reactor and excitation control is proposed for stabilization of power systems.The first control action, incorporating dynamic braking resistor and shunt reactor,is applied for initial stabilization of system and the second action, incorporating excitation control,is applied subsequently for stabilizing remaining small amplitude oscillations following the first swing.The time-optimal control is derived as a function of synchronous machine power, rotor angular position and speed deviation which depend on the conditions existing at the time.The strategy has been applied here to three different cases of multimachine power sysyems.Results show that the application of the proposed strategy involving sequential control actions is a simple and effective method for achieving power system stability.It has also been found that the conrtol scheme is feasible for online application using relatively little hardware and simple local measurements.

ABBREVIATIONS

AIEE	American Institute of Electrical Engineers
ASHG	Ashuganj High Voltage Grid
ASMG	Ashuganj Main Grid
AVR	Automatic Voltage Regulator
BHEG	Bheramara Grid
BPDB	Bangladesh Power Development Board
BPS	Bangladesh Power System
BOGG	Bogra Grid
d-axis	Direct axis
DC	Direct Current
EXC.	Exciter
Equ.	Equation
Fig.	Figure
GHHS	Ghorasal High Voltage Grid
GHMG	Ghorasal Main Grid
Gov.	Governor
GOAG	Goalpara Grid
IEEE	Institution of Electrical and Electronic Engineers
KAPG	Kaptai Grid
MW	Megawatt
MVAR	Megavar
PMP	Pontryagin's Minimum Principle
PU	Per unit
PSS	Power System Stabilizer
q-axis	quadrature axis
SIKG	Sikalbaha Grid
SIDG	Siddhirganj Grid
SHAG	Shahjibazar Grid
TC	Time Constant

LIST OF NOTATIONS

$A_1 - A_0$	PSS high frequency filter constant
BD	Susceptance
D	Differential Operator
d	Damping Constant
E	Internal Voltage of Machine
E_{fd}	d-axis generator field voltage (exciter output voltage)
E_q'	q-axis transient internal voltage
G	Conductance
i_d	direct-axis current
i_q	q-axis current
J	Performance measure
K	total effective speed-governing system gain
$K_1 - K_7$	General Model parameters
K_F	Exciter Stabilizer gain
K_E	Exciter Constant related to self-excited field
K_A	Voltage regulator gain
M(or H)	Inertia Constant
n	PU angular frequency deviation
P_{in}	input power
P_o	Output power
P_b	Power dissipated in brake
P_e	Electrical output
P_a	Accelerating power
P(t)	Costate
P_{GV}	Power at gate output
P_{max}, P_{min}	Power limits
r_a	armature resistance

r_b	braking resistance
s	Differential Operator
sgn	Sign dependant
$T_1 - T_7$	Time Constantst
t	time
T_E	Exciter time constant
T_F	Exciter Stabilizer TC
T_A	Voltage Regulator TC
T_R	Regulator input filter TC
T_{do}	Open circuit transient time constant
T_i	Input Torque
T_e	Airgap Torque
U	'the union of'
u	control vector
V_{REF}	Voltage regulator reference voltage
V_S	PSS output
V_{SI}	PSS input
V_T	Generator terminal voltage
V_F	Excitation system stabilizer output
V_{ERR}	Voltage error signal
V_d	d-axis voltage
V_q	q-axis voltage
V_{fd}	Field voltage at d-axis
V_{fq}	Field voltage at q-axis
X	reactance
x_d	d-axis reactance
x_q	q-axis reactance
x_d'	d-axis transient reactance
x_{ff}	total field reactance
x_{afd}	d-axis mutual reactance of armature and field
x_{afq}	q-axis mutual reactance of armature and field

X_T	Shunt reactor
Z_{t1}	series impedance of line
α	control value at t=0
ω	speed of machine
$\Delta\omega$	speed deviation
ω_b	base speed
Σ	switch curve
Ψ	flux linkage
σ_1, σ_2	target state limit
δ	rotor angle
δ_i	rotor angle of i-th machine
δ_r	rotor angle of reference machine
φ	phase
$\in$	'in the region of'

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The general trend in electric power production to-day is toward interconnected networks of transmission lines linking generators and loads into large integrated systems. Disturbances at any point is likely to propagate through the rest of the system and this may result in failures of machines and equipments unless adequate safety measures are incorporated. For reliable generation and transmission of electrical energy, it is essential that the total power system be stable subsequent to such disturbances. Application of suitable control techniques to improve the transient stability of power systems shall be investigated in the present work.

1.2 POWER SYSTEM STABILITY

According to Kimbark [2], "Power system stability is a term applied to alternating current electric power systems, denoting a condition in which the various synchronous machines of the system remain in synchronism or 'in step' with each other. Conversely, instability denotes a condition involving loss of synchronism or falling 'out of step'". Power system stability may be classified into steady-state stability, transient stability and dynamic stability depending on the order of magnitude and type of disturbances.

Steady state stability is the ability of the power system to maintain transfer of power without loss of synchronism as the amount of power transferred is changed gradually.The change in power level must occur slowly enough so that regulating devices are able to respond. It is also assumed that inertia effect is negligible.

Transient stability is the ability of a power system to maintain stability in the event of a sudden large change in load occasioned by system switching or by faults. Usually the regulating devices are not fast enough to respond during this transient period and nonlinear modes of system operation may be encountered. In this case system is likely to lose stability unless an effective countermeasure is taken, e.g. dynamic resistance braking or fast valving/load shedding.

Dynamic stability is the ability of the power system to maintain stability for relatively small disturbances and to prevent oscillations. Dynamic instability generally occurs due to lack of damping torque. A typical example would be the low frequency oscillations that may occur in the large interconnected power systems.

1.3 STABILITY STUDIES

Transient stability studies constitute one of the major analytical approaches to study of power system electromechanical dynamic behavior. These studies are aimed at determining if the system will remain in synchronism following major disturbances such as system faults, sudden and large load changes, loss of generating units, or line switching. Present day power systems are vast, heavily interconnected,incorporating hundreds of machines which can dynamically interact through their extra-high voltage networks. These machines have associated excitation systems and turbine-governing control systems. In transient stability studies these associated components must be modeled in order to properly reflect the correct dynamic response of the system to certain disturbances.

Dynamic and steady state stability studies are less extensive in scope and involve one or just few machines undergoing slow or gradual changes in operating conditions. Therefore, dynamic and steady-state stability studies concern the stability of the locus of essentially steady-state operating points of the system. The distinction made between steady-state and dynamic stability studies is really artificial since the stability problems are the same in nature, they differ only in the degree of detail use to model of the machines. In dynamic stability studies, the excitation system and turbine-governing system models are represented along with synchronous machine models. Steady-state stability studies use a very simple generator model which treats the generator as a constant voltage source. The solution technique is to examine the stability of the system under incremental variations about an equilibrium point. The nonlinear differential and algebraic equations for the system can be linearized which are then solved to determine whether the machines will remain in synchronism following small changes from the operating point.

Transient stability studies are much more commonly undertaken thereby reflecting their greater imprtance in practice. Such problems involve large distubnces which do not allow the linearization process to be used and the nonlinear differential and algebraic equations must be solved. Transient stability problems can be subdivided into first swing and multiswing stability problems. First swing stability study is based on a reasonably simple generator model without representation of the control systems. Usually the time period under consideration is one second after the system fault. Multiswing stability problems extend over a longer period and therefore must consider effects of generator control systems which affect machine performance during that time period.

1.4 EQUILIBRIUM STUDIES

During steady operation of a power system, there is equilibrium between the mechanical power input of each generator and the sum of the losses and the electric power output of that generator. Similar equilibrium exists for each generating plant, for each area and for the entire power system.

This equilibrium is destroyed by a disturbance. A short circuit near a generating plant greatly decreases the electric power output of the plant and increases its losses by a lesser amount, but it has no immediate effect on the mechanical input. The excess of input over losses and output (called accelerating power) goes into increasing the kinetic energy of the generating units in the plant. Similarly, excess of output and losses over input (decelerating power) decreases the kinetic energy.

Accelerating power divided by the inertia constant equals angular acceleration. The time integral of angular acceleration is the angular speed deviation. The time integral of angular speed deviation is the change of angle relative to a reference axis rotating at rated speed. If the relative angle between two generating units become too great, synchronism is lost.

Note that the first sign of impending trouble is acceleration. The speed deviation appears later and the angular change still later. Therefore, detection of angular acceleration is the most promising way of quickly initiating preventive action.

Disequilibrium of power can occur as a result of either a change of mechanical input or of a change of electrical output. However, from a practical point of view, it is obvious that changes in electrical output can occur almost instantaneously because of changes in the network, whereas the mechanical input cannot change nearly so fast. Although a sudden change in output should properly be counteracted immediately by a sudden change of input of equal amount, this cannot always be accomplished in practice rapidly enough to prevent instability. This fact suggests that after disequilibrium has been caused by a sudden change in the network, it must be counteracted by another sudden change in the network. The second sudden change may be stopped when the necessity for it has disappeared either through slower readjustment of mechanical input or through the disappearance of the first change in the network.

1.5 METHODS OF POWER SYSTEM TRANSIENT STABILIZATION

The swing equation for a synchronous machine can be written as

$$M \frac{d^2\delta}{dt^2} + D \frac{d\delta}{dt} = P_{in} - P_o \qquad (1.1)$$

where

M = inertia constant

D = damping constant

δ = rotor angle

P_{in} = mechanical input power

P_o = output power = $\frac{EV}{X} \sin \delta$

$P_{in} - P_o = P_a$ = accelerating power

At the steady state operating point of the machine, both the velocity of the machine and the accelerating power P_a are zero while the machine rotor angle is constant. By changing P_a, E and X etc., the stability of the system can be enhanced. As the means of transient stability augmentation, the following approaches are reported in the literature:

1) change in mechanical input
2) generator dropping
3) load shedding
4) switched series capacitor
5) switched shunt capacitor
6) braking resistor
7) forced excitation
8) independent pole switching of circuit breaker
9) modulated DC link.

1.5.1 Change in Mechanical Input [15]

The mechanical input varies in accordance with the speed-governor action following deviations from scheduled frequency or as a result of the movement of intercept valves to reduce the mechanical input of the prime mover. This scheme improves first swing stability for the generator that tends to acquire excess speed during severe disturbance. However, instability can occur during the later swings if the opening and closing of the intercept valves are not properly timed [6]. Modern electro-hydraulic turbine governing system have the ability to close turbine valves to reduce unit acceleration during severe faults. Immediately upon detecting the differences between mechanical input and electrical output, control action initiates the valve closing which reduces the power input.

In modern tandem compound turbine-generator an effective way to reduce turbine power rapidly is to close the intercept valves to stop the steam flow. The valves control the steam flow to the intermediate pressure and low pressure turbine elements, which in combination generates approximately 70% of the total power. To avoid the mechanical stresses in the boiler because of sudden closing of the intercept valves, the modern practice is to divert the steam into the condenser. This is done when power/load unbalance circuit detects the unbalance above certain predetermined level.

1.5.2 Generator Dropping [15]

The best use of generator dropping is in a sending area to counteract the loss of a large load in that area. The amount of generation dropped should roughly equal the amount of load lost.

In the case of loss of large load, obviously the system would become unstable if no measures were taken. Generation is dropped as soon as possible. In the absence of damping, the remaining generators would continue to oscillate. However, there is damping torque which finally brings the generators to rest.

Generator dropping is sometimes used as a cheap substitute for braking, but it cannot be as accurately controlled as that of braking or excitation.

1.5.3 Load Shedding [15]

Load Shedding is required to counteract loss of generation in a receiving area. Power companies should encourage the acquisition of loads that, by contract provisions are interruptable for short times without notice in return for a low energy change.

Load shedding followed by restoration can be obtained by any of the following methods:

1) opening of one or more selected feeders followed by reclosure,

2) temporary depression of voltage by an intentional short circuit followed by its clearing,

3) temporary depression of voltage by connection of a shunt reactor followed by its disconnection.

The usual control of load shedding by under frequency relays is too slow for preservation of transient stability. Transferred signals from generator circuit breakers or from fault-clearing relays on interties should be used, subject to supervision by the power output of the generator or of the power delivered by the interties.

1.5.4 Switched Series Capacitor

The series capacitor switching as a means of quenching transient oscillations in a power system has been analyzed in several papers [8,9,10].

Conceptually, the capacitor reduces the inductance of the transmission line in order to increase its energy transfer capabilities. Accurate timing of the capacitor insertion and removal are very critical if the disturbed state of the power system is to be transferred to its post-fault stable state [11].

Rama Rao [12] and Miniesy [13] have considered the problem of finding the optimal value of capacitance for particular disturbance. The difficulty encountered by these investigators has been in predetermining the optimal value of the capacitance and the duration of switching independent of the type of disturbance.

1.5.5 Switched Shunt Capacitors or Reactor

It has been found that switching on or off shunt reactors [15,16] can aid momentarily in balancing energy transfer. The shunt reactor switching is also potentially useful for extending the stability margin of a generator (or group of generators) which tend to decelerate very rapidly during severe disturbances.

1.5.6 Dynamic Braking

The dynamic braking resistor can be viewed as a fast load injection to absorb excess transient power of an area which arises due to a severe system disturbance. It has generally been studied as a shunt resistor load connected at a generator site and its energy absorbing capability is limited by the maximum temperature rise of the braking resistor material.

1.5.7 Excitation Control

In this scheme, the restoring synchronizing forces are increased through forced excitation to boost the internal machine flux. When a fault occurs on a system, voltage at all buses are reduced. At generator terminals, the reduced voltages are sensed by Automatic Voltage Regulators which act within the excitation system to restore the generator terminal voltages. The general effect of the excitation system is to reduce the initial rotor angle swing following the fault. This is accomplished by boosting the voltage applied to the field winding of the generator through the action of the amplifiers in the forward path of the voltage regulators. The increased air-gap flux exerts a restraining torque on the rotor which tend to slow down the rotor motion.

Modern excitation systems can be effective in two ways: in reducing the magnitude of the first swing and by ensuring that the subsequent swings are smaller than the first. The later is an important consideration in present day large interconnected power systems. Situations may be encountered where various modes of oscillations reinforce each other during later swings, which along with the inherent weak systems damping can cause transient instability after the first swing. With the proper compensation, a modern excitation system can be very effective in correcting this type of problem.

1.5.8 Independent Pole Switching of Circuit Breaker [15].

In recent years, independent pole tripping of the circuit breakers is used to minimize the severity of the multiphase faults. In this scheme, each of the three phases of the circuit breaker is tripped independently of each other to reduce the probability of total breaker failure. This operation effectively improves the system stability margin.

1.5.9 Modulated DC Link [15].

In some cases where available, the dc link may be used within its capacity to offset energy imbalance that arise in ac system due to severe disturbance [33]. Transmission and generation system configuration dictate the relative effectiveness of rapid dc modulation. An ideal situation would be one in which the dc line is the major tie line between two ac systems.

From the above brief description of different methods of transient stabilization, it can be said that the individual or collective use of the various fast control means can effectively improve the transient stability margin.

1.6 LITERATURE REVIEW

The phenomenon of stability of synchronous machine operation has received a great deal of attention in the past. In this section, a detailed survey on braking resistor and shunt reactor control of power system stability is presented first and works on excitation control are given thereafter.

1.6.1 Breaking Resistor and Shunt Reactor Control

Practical use of dynamic braking resistors for transient stability augmentation has been reported in USSR [18,19] and also in Japan [20]. In these cases braking resistor has been used repeatedly to absorb the transient excess energy.

The Peace River 500 KV transmission system [21] maintained the stability following faults by employing braking resistors. The Four Corner Plant (Arizona Public Service Company) [22] have made similar use of braking resistor to maintain stability margin.

A 1400 MW [23] dynamic braking resistor installed at the Bonneville Power Administration's (BPA) Chief Joseph Substation is used to enhance system stability in the Pacific Northwest. In reference [24] the physical and electrical characteristic of the brake as well as the control system for its operation are discussed.

W.A. Mattelstadt [29] showed that dynamic brake is more suitable for slowing a diverging generator group than it is for damping system oscillations.

E.W. Kimbark [15] discussed the improvement of power system stability by changes in the network such as connecting shunt resistor brakes, disconnecting generator or loads and inserting series capacitors and shunt reactors. Measurements of angular differences is the only criteria to use these measures.

A microprocessor based optimal quality control of dynamic braking has been described by Fei Yiqun [30]. In this control scheme the brake has been removed not at $\delta=0$, but at the suitable time of $\omega<0$ before circuit reclosing.

Optimum bang-bang control of series and parallel resistors to improve power system transient stability has been reported by K. Nakamura and S. Muto [24].

A Rahimi [25] used Pontryagin's minimum principle to develop feedback control law for switching the braking resistor. Some practical aspects of implementation of the control scheme and computer simulation tests are presented in this paper.

In reference [26] a braking resistor has been used to improve the transient stability of a one machine, infinite bus system. The minimum angle and minimum-norm aiming strategies are used to provide explicit feedback solution to the control problem. It shows improvement in critical clearing time.

K.K. Oey et al [27] gives details of an experimental investigation in which a benchtop model is used for the development and evaluation of transient stability control strategies. A three-phase shunt resistor inserted repeatedly to a computer driven micro-machine to improve stability.

In a recent paper T.K. Nag Sarker et al [28] presented the improvement of transient stability with the help of a full wave thyristor controlled dynamic brake. Investigations include the development of a mathematical model of half wave thyristor controlled dynamic brake.

U.O. Aliyu [31] used dynamic braking resistor and reactor switching to show the systematic corrective control approach for transient emergency state problem of the power system. In this work a local control strategy is presented which switches a braking resistor and a shunt reactor alternately depending on the velocity deviations. The resistor absorbs the excess energy while the machine accelerates and reactor reduces the output power when it decelerates. The switching strategy is determined from an estimate of the critical clearing time through Lyapunov's direct method which again is obtained from the reduction of the multimachine system to a single machine equivalent.

S.S. Joshi and D.G. Tamaskar [32] has developed a strategy depending on the speed deviation signal and utilized it for automatic single or multiple insertion of the braking resistor, whenever required. Micromachine model of the power system is used for this purpose. The application of the brake when the magnitude of the swing become smaller may aggravate the situation. Because the resistor may absorb the excess energy than required if the insertion and switching out of the resistor is not precise. In this situation some other methods suitable for controlling small swings may be preferable.

1.6.2 Excitation Control

Considerable attention has been given to the excitation system study and its role in improving power system stability. Early investigators realized that the so-called "steady-state" power limits of power networks could be increased by using the-then available high-gain continuous acting voltage regulators [52]. A transient stability program has been reported including the effects of regulator, exciter and governor response by Dyrkacz, Young and Maginniss [53]. In reference [54], the researchers showed the effect of excitation systems on stability of synchronous machine.

Increasing attention has thus been focused on the effects of excitation control for the damping of oscillation which characterize the phenomena of stability. In particular, it has been found useful and practical to incorporate transient stabilizing signals derived from speed, terminal frequency or power [55,56] superposed on the normal voltage error signal of voltage regulators to provide additional damping.

A number of papers by F.R. Schleif et al described the excitation control scheme [56,57].

The phenomena of stability of synchronous machines under small perturbations is explored by examining the case of a single machine connected to an infinite bus using thyristor-type excitation systems [58].

M. Venkata Rao and M. P. Dave of India described methods of non-linear gain excitation control for a single variable [59] and for a number of variables [60] and then these methods were applied to the optimal stabilization of a multimachine system.

In another study of excitation system [61], a classical representation showed a certain generator to be stable, while detailed representation of the generator indicated that loss of synchronism results.

In the past decade, some studies of the application of adaptive control topology to excitation control have been reported with rather dramatic results. Based on linear model, either the linear optimal state feedback control,strategy is used to minimize a properly selected quadratic performance index [62,63] or the minimum variance control strategy is used [64,65].

The design of an excitation self tuning controller for a generator connected to an infinite bus through long line has been proposed by Daozhi Xia and G.T. Heydt [66].

Yao-nan Yu et al proposed an output feedback excitation control to stabilize the torsional oscillation due to subsynchronous resonance [67,68]. However, Yao-nan Yu and H.A.M. Maussa earlier proposed optimal power system stabilization through excitation control [69].

In reference [70], the authors present a generalized excitation control design that ensures not only a desired damping of the critical electromechanical modes of oscillation but also the zeroing of the terminal voltage error independent of terminal voltage excursions. The excitation system consists of a compensation transfer function utilizing the machine speed or terminal frequency and/or electrical power.

J.Y.H. Chen and G.L. Kusic [71] introduces a stabilization method for the design of linear optimal controllers which can stabilize a directly-coupled multimachine system via excitation control. A systematic modeling method is first developed to formulate the system into state space form with directly measurable state variables. With this form, the stabilization of the system is converted to a linear-quadratic Gaussian problem. Next a model reduction algorithm is developed.

A quasi-optimal control of excitation of multimachine power system has been proposed in [47]. There the authors reported a simple control strategy of excitation control to enhance power system stability under small disturbance.

1.7 MOTIVATION OF PRESENT WORK

From the literature review, it is apparent that a number of work has been reported ranging from theoretical studies and complex simulations to testing of various switching algorithm for braking resistor control and excitation control of power system stability problem. All the previous studies as described in literature review are aimed only to control the stability by using one of the techniques independently. Efforts have been made so far to improve power system stability by using either transfer admittance control or excitation control.

From such studies, it is apparent that transfer admittance control is very effective in controlling first swing instability. A dynamic control strategy depending only on machine speed deviation is easily realizable [31,32], but the determination of threshold values is not straight forward.

Optimum strategies for determination of switching times are complicated [25.26] and handicapped in terms of online application. So the real problem has been and still is the determination of easily implementable best or optimal switching strategy.

A simple closed loop strategy [1] involving dynamic brake and shunt reactor has been reported which is efficient and feasible for online application. But this strategy is suitable for large oscillations. For smaller oscillations, braking resistor may worsen the situation if it is not inserted in the system and taken off the system at proper times. This requires very fast and frequent on and off of the brake which may not be feasible from practical point of view.

Though the first swing can be reduced by dynamic braking control, the system is still oscillatory in nature with smaller swings. To stabilize these smaller swings, an excitation control scheme has been reported in the literature [47].

Excitation control of both first swing and subsequent swing have already been proposed in several works. But except for transient stability studies involving faults with long clearing times, the effect of the excitation system on the severity of the first swing is relatively small. That is, a very fast, high-response excitation system will usually reduce the first swing by only a few degrees or will increase the generator transient stability limit (for a given fault) by a few percent.

Thus in the present research, the braking resistor and shunt reactor control for first swing and the excitation control for subsequent swings are proposed.

For transient stability the time duration is very small. So the application of the control actions must be very quick. Also fast control strategies should not involve any offline computation, the number of data measurement must be minimum and the data to be measured should be local to the disturbed system. That is from online application view point the control algorithm must be simple and fast. Because of the nonlinearities, complexities and size of power systems optimal control strategies is not feasible as these involve heavy computation time and most of the time a closed-loop solution is not feasible. But for online effective control of the system the control must be closed loop. That is why suboptimal control strategies are proposed.

In this research, two minimum-time quasi-optimal control strategies are applied sequentially for transiently disturbed systems. One strategy is for dynamic braking and shunt reactor control and the other one is for excitation control.

1.8 THESIS OBJECTIVES

This thesis addresses the power system first swing and subsequent swing stability enhancement aspect. A coordinated scheme with dynamic braking resistor-shunt reactor and excitation control is used for this purpose.

The specific objective of the thesis are as follows:

1. Development of a quasi-optimal feedback control strategy for using braking resistor and switching reactor control to improve power system stability.

2. To study the effect of the control strategy on a single machine infinite bus system.

3. To study a coordinated braking resistor and shunt reactor control for transient first swing stability and excitation control for subsequent swing stability.

4. Verification of the effectiveness of the coordinated sequential applicable quasi-optimal, time-minimum feedback control strategy on multmachine system showing stability on both first swing and subsequent swing region.

5. To study the effectiveness of the coordinated control scheme on BPDB (Bangladesh Power Development Board) system by simulating three phase fault at different buses.

CHAPTER 2

DYNAMIC MODELS FOR POWER SYSTEM STUDIES

2.1 INTRODUCTION

The dynamics of a power system is inherently nonlinear and thus, its complex representation, especially in the transient state, will be too complex for the purpose of formulating a realistic online control algorithm. To circumvent this problem, an appropriate choice of simplified mathematical models which adequately describe the dominant behavior of the system is essential. Typically there are several interacting subsystems and their mathematical representations generally involve a set of high order nonlinear differential equations. For this reasons, a simplified model is traditionally used to study the power system dominant dynamic behavior in transient state.

2.2 MODEL OF POWER SYSTEM COMPONENTS

The schematic representation of a single machine infinite bus system is shown in fig. 2.1. The turbine-governor and the excitation system are shown separately. The models for the various components, as reported in the literature, are discussed below.

2.2.1 Synchronous Machine Model [45]

Fundamental equations of synchronous machines were derived by Park and others years ago. Park's equations have the simplest form and are most well-known. His voltage equations are described by a coordinate system consisting of a d-axis or direct axis and a q-axis or quadrature axis fixed in quadrature with respect to the d-axis. For a dual-axis excited synchronous generator, two field winding is shown in two axis. Park's synchronous machine may be schematically shown as fig. 2.2 and equations are given in Appendix A.

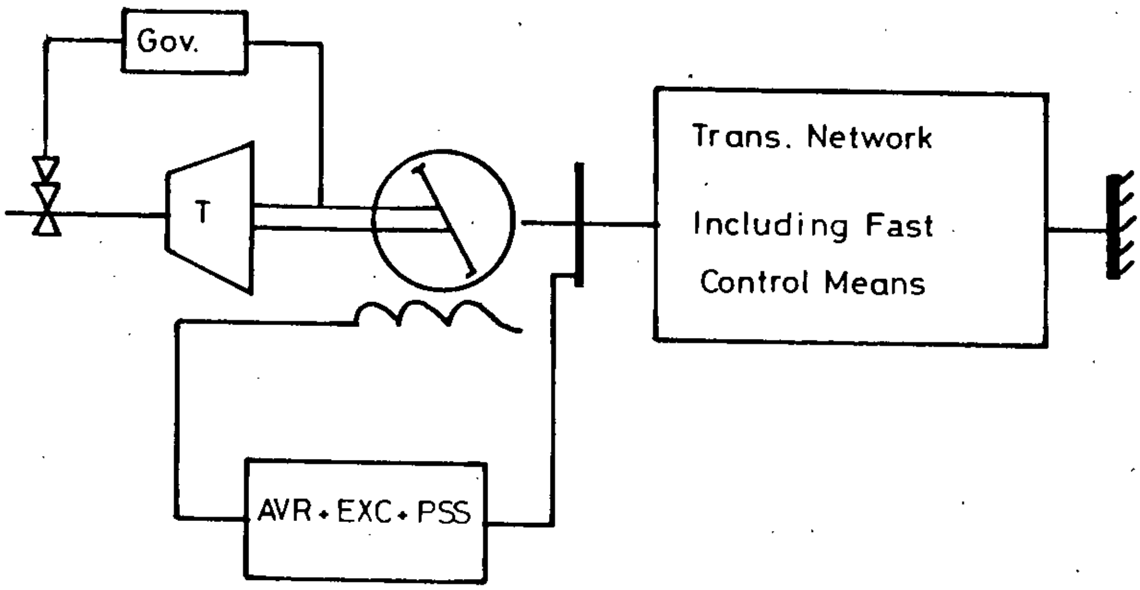


Fig.2.1 Schematic Diagram for Single Machine Infinite Bus System.

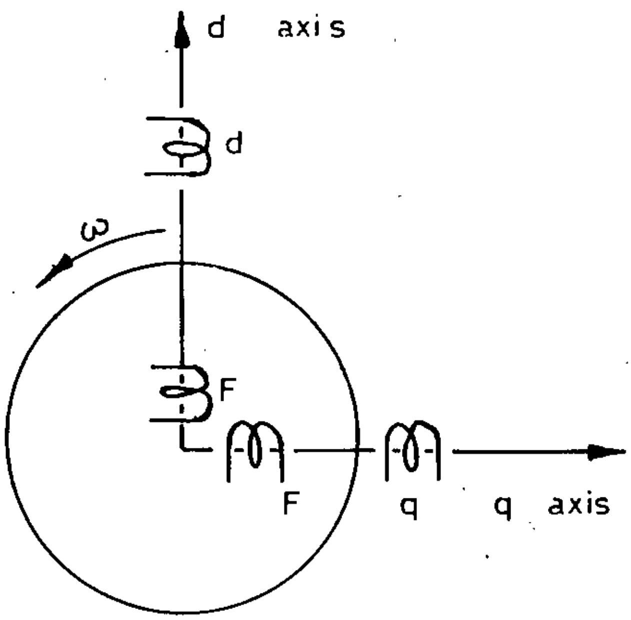


Fig 2.2. PARK'S SYNCHRONOUS MACHINE

Considering equations (A.1.3) and (A.1.4) of Appendix A, multiplying both sides of the equations by $\frac{x_{afd}}{r_{fd}}$ and $\frac{x_{afq}}{r_{fq}}$, gives

$$E_{fd} = x_{afd}\, i_{fd} + \frac{x_{afd}}{\omega_b r_{fd}} D\Psi_{fd} \qquad (2.1.1)$$

$$E_{fq} = x_{afq}\, i_{fq} + \frac{x_{afq}}{\omega_b r_{fq}} D\Psi_{fq} \qquad (2.1.2)$$

Now substituting in (A.4) for $x_{afd}\, i_d$ from (2.1.1)

$$E_q' = E_{fd} - \frac{x_{afd}}{\omega_b r_{fd}} D\Psi_{fd} - (x_d - x_d')\, i_d \qquad (2.2)$$

Differentiating (A.3.2) gives

$$DE_q' = \frac{x_{afd}}{x_{ffd}} D\Psi_{fd}$$

$$D\Psi_{fd} = \frac{x_{ffd}}{x_{afd}} D E_q'$$

Substituting (2.3) and (A.9) in (2.2),

$$E_q' = E_{fd} - \frac{x_{ffd}}{\omega_b r_{fd}} DE_q' - (x_d - x_d') i_d$$

$$= E_{fd} - T_{do}' DE_q' - (x_d - x_d') i_d$$

or,

$$\frac{dE_q'}{dt} = \frac{1}{T_{do}'} [\, E_{fd} - E_q' - (x_d - x_d') i_d \,] \qquad (2.4)$$

which is the quadrature axis internal voltage equation. Following the similar approach the direct axis internal voltage E_d' can be expressed as

$$\frac{dE_d'}{dt} = \frac{1}{T_{qo}'} [- E_d' + (x_q - x_q') i_q] \qquad (2.5)$$

where T_{do}' and T_{qo}' open circuit transient time constant.

Equation (2.4) and (2.5) are approximate electrical representation of the synchronous machine.

2.2.2 Mechanical Rotating System Model

The mechanical rotating system is normally represented as a single solid shaft so that the torsional oscillation effects are neglected. Thus, the mechanical rotating system is essentially modeled by a second order differential equation to reflect the dominant electromechanical oscillations during the transient disturbances. This is expressed as

$$MD^2\delta + dD\delta = P_m - P_e \qquad (2.6)$$

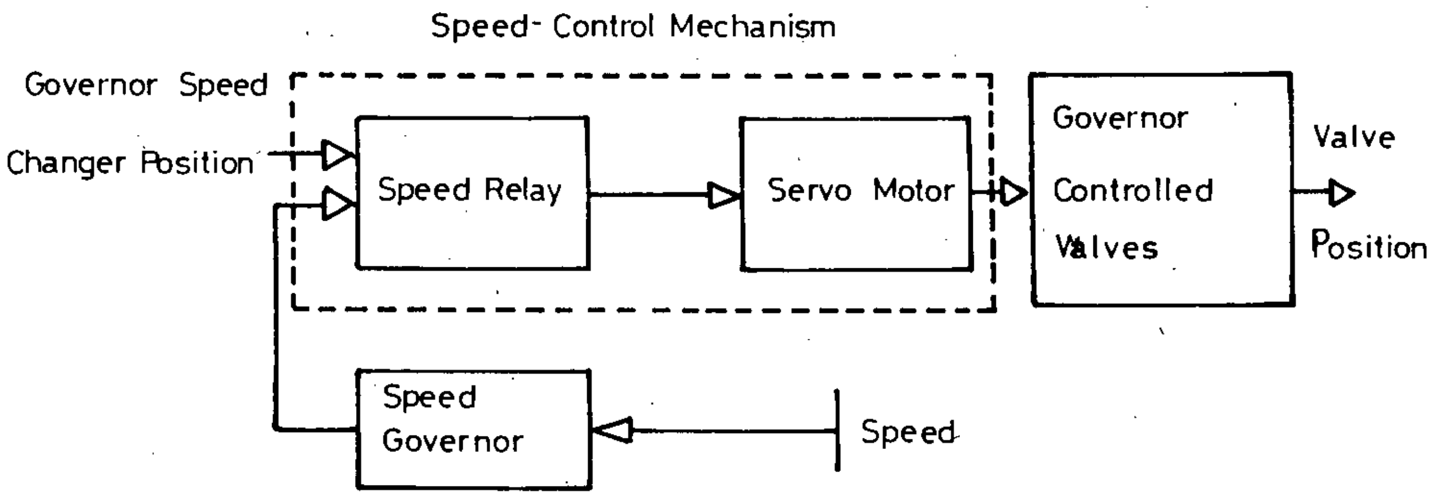
where,

δ	:	rotor angle,
M	:	inertia constant,
d	:	damping constant,
P_m	:	prime mover mechanical input,
P_e	:	electrical output.

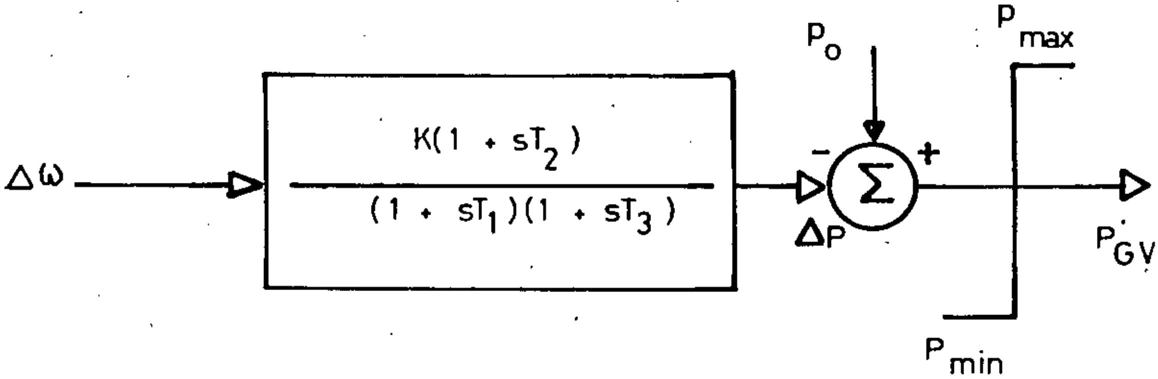
2.2.3 Speed-Governing System [39]

A typical mechanical-hydraulic speed-governing system consists of a speed governor, a speed relay, a hydraulic servomotor and governor-controlled valves [39] which are functionally related as shown in figure 2.3(a).

The speed-governor produces a position which is assumed to be linear, instantaneous indication of speed. A signal is obtained from the governor speed changer of fig. 2.3(a). It represents a composite load and speed references and is assumed constant over the interval of a stability study. The speed relay is represented as an integrator with time constant T_1 and direct feedback. The servomotor is represented by an integrator with time constant T_3. The servomotor moves the valves. Assuming linear characteristic the block diagram is given in figure 2.3(b). This model shows the load reference as an initial power P_0. This initial valve is combined with the increments due to



(a)



(b)

Fig. 2.3 Speed Governing System: (a) Functional Block Diagram; (b) Mathematical Representation speed deviation $\Delta\omega$ to obtain the total power P_{GV}, subject to the time lag T_3, introduced by the servomotor mechanism. The total effective speed-governing system gain is K.

2.2.4 Steam Turbine System [39]

The turbine system is comprised of high pressure, intermediate pressure and low pressure stages with reheat between the stages. All compound steam turbine systems utilize governor-controlled valves at the inlet to the high-pressure (or very high pressure) turbine to control steam flow. The steam chest and inlet piping to the first turbine cylinder and reheaters and cross-over piping downstream all introduce delays between valve movement and change in steam flow. The principal objective in modeling the steam system for stability studies is to account for these delays. Flows into and out of any steam vessel are related by a simple time constant.

The steam turbine block diagram is given in figure 2.4. The time constants T_4, T_5, T_6 and T_7 represent delays due to the steam chest and inlet piping, reheater 1, reheater 2 and crossover piping respectively. K_1 - K_7 are general model parameters which represent portions of the total turbine power developed in the various cylinders.

In the transient stability studies, the time period of interest is very small. But the time constant of turbine-governor system is large. That is why their dynamics has not been considered in this study.

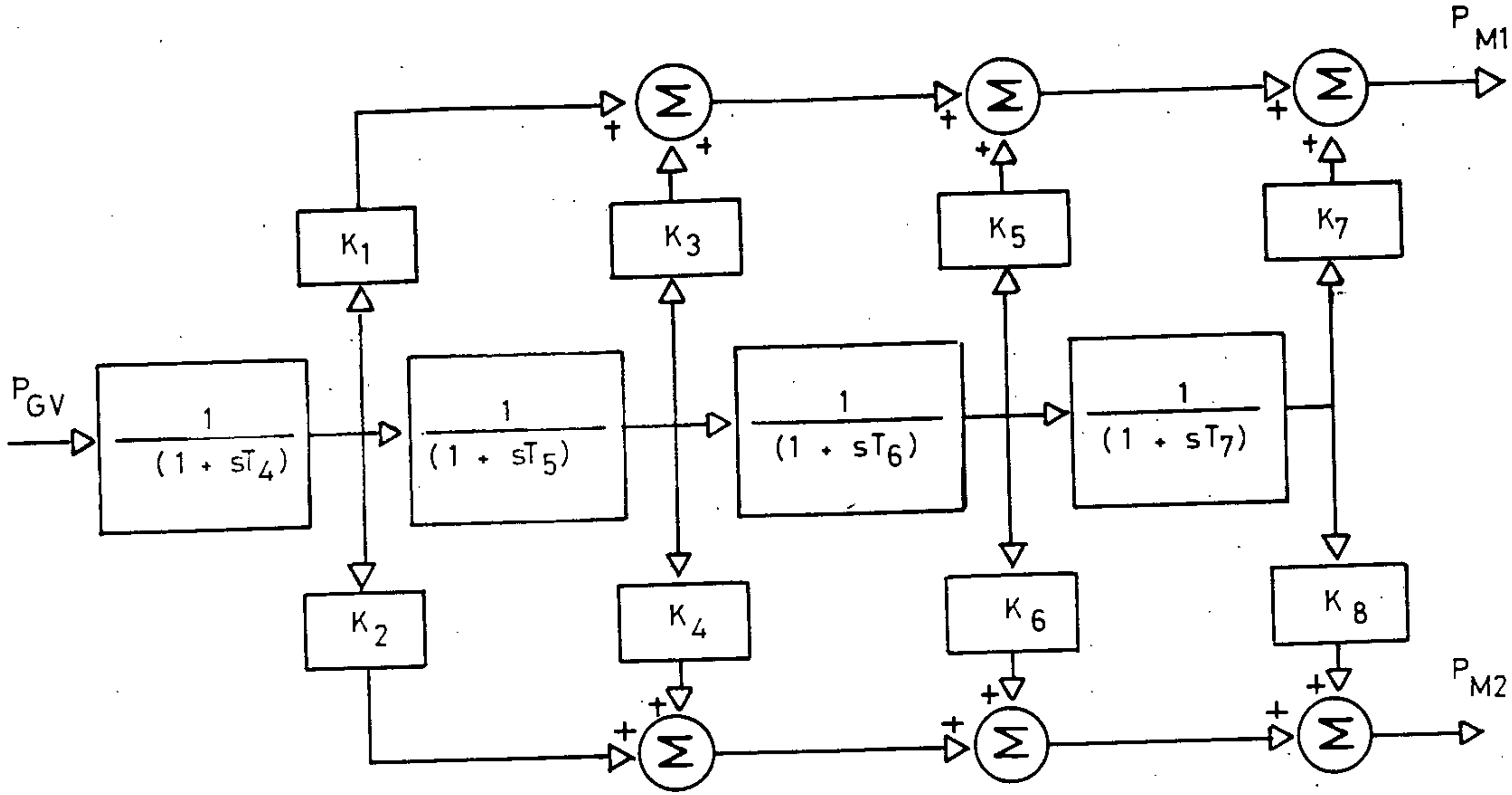


Fig. 2.4 Steam Turbine Block Diagram

2.2.5 Excitation System Model [40,45]

When the behavior of synchronous machines is to be accurately simulated in power system stability studies, it is essential that their excitation systems be modeled in sufficient detail. The desired models must be suitable for representing the actual excitation equipment performance for severe disturbances as well as small perturbations.

The general block diagram in figure 2.5(a) indicates the various generator excitation subsystems which are customarily represented in electric power system studies. They include a terminal voltage transducer and load compensator, a voltage regulator, an exciter and excitation system stabilizer. In many present-day systems the exciter is a dc generator driven by either the steam-turbine or an induction motor. An increasing number are solid-state systems consisting of some form of rectifier or thyristor supplied from the ac bus or from an alternator-exciter. The voltage regulator is the intelligence of the system and controls the output of the exciter so that the generated voltage change in the desired direction. In most modern systems the voltage regulator is a controller that senses the generator output voltage- then initiates corrective action by changing the exciter control in the desired direction.

The voltage regulator and exciter are modeled here by an IEEE type 1 excitation system as shown in figure 2.5(b). The first block from the left represents the transfer function of rectifier and filter with time constant T_R of the measured terminal voltage V_T, which has a very small time constant. The voltage error Δv_t is obtained from a comparison of V_T with a reference voltage V_{REF} at the first summer. Other signals V_{PS}, such as supplementary excitation to improve the dynamic stability of a power system, can be also added to that summer.

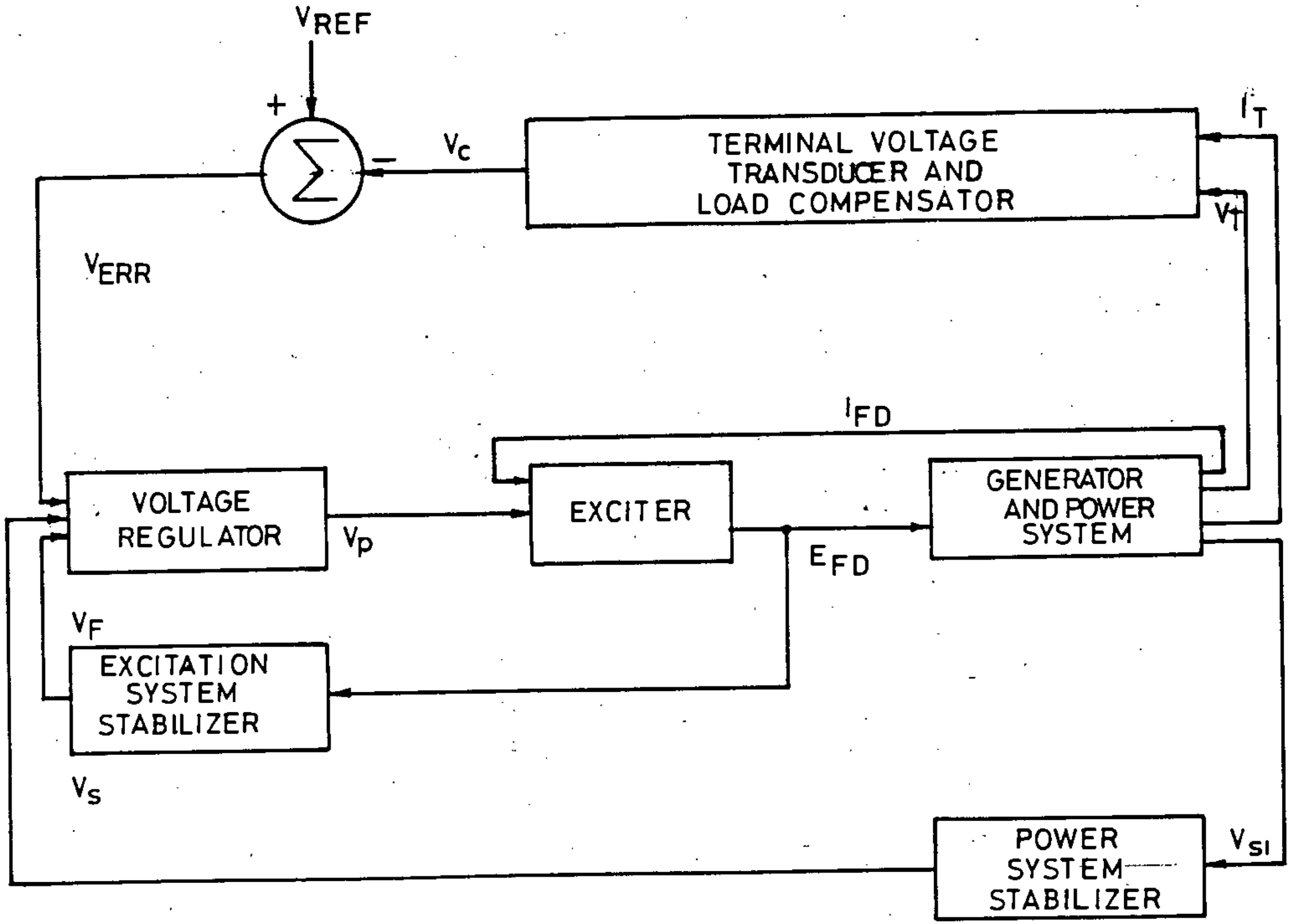


Fig. 2.5(a) General Functional Block Diagram for Generator Excitation Control System

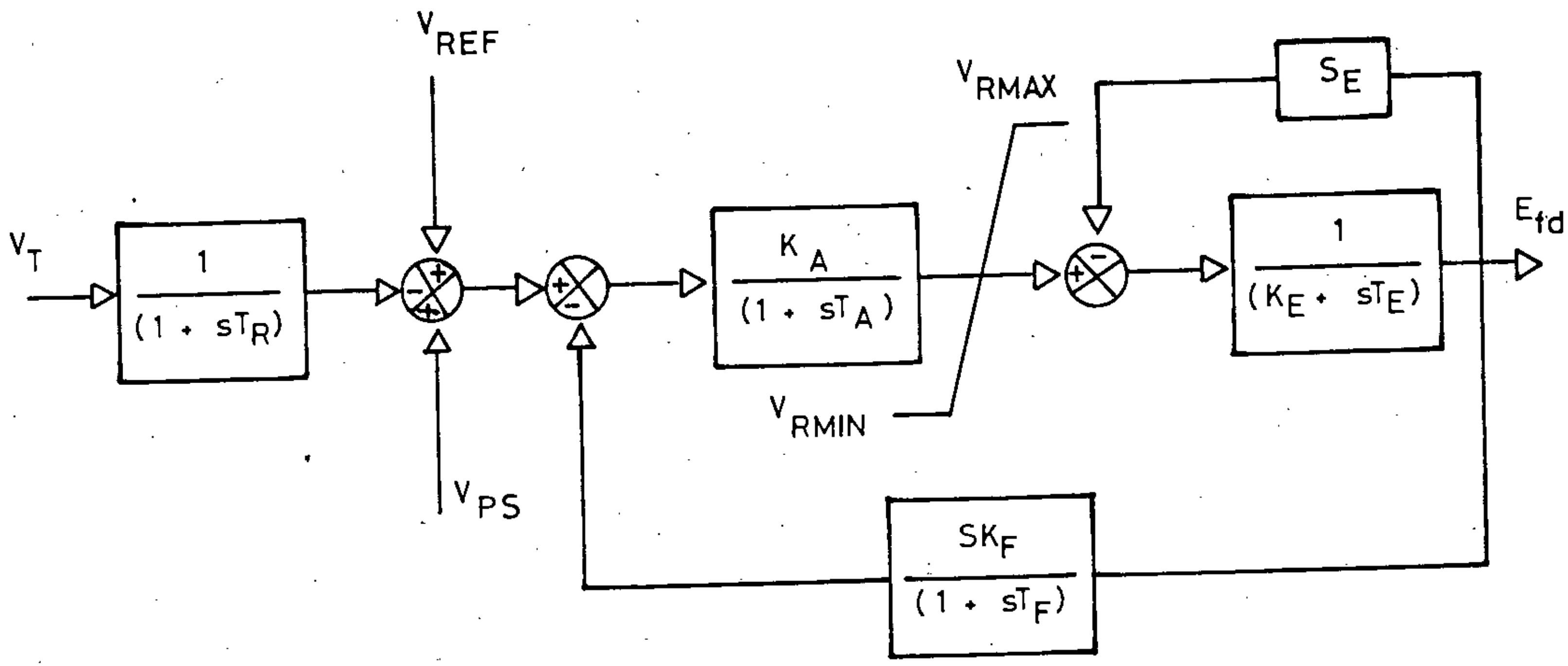


Fig. 2.5(b) IEEE Type 1 Excitation System

The block after the second summer represents the transfer function of a voltage regulator that has a time constant T_A and a gain K_A. The linear proportionality and the ceiling voltages V_{Rmax} and V_{Rmin} are also shown.

The last block on the forward branch with a negative feedback S_E represents the transfer function of the exciter. It has an output voltage E_{fd} corresponding to the generator internal voltage E_{fd} of equation (A.3.1). There are two constant K_E and T_E of this block, but T_E is not itself a time constant because of the presence of the other constant K_E.

There are two negative feedback loop of the Type 1 excitation system. One of them has a factor S_E that represents the saturation effect of the exciter. This alters the amplifier voltage V_R by an amount S_E E_{fd}. The other includes a time constant T_F and a gain K_F of the excitation system stabilizer.

2.2.6 Power System Stabilizer [40]

Fig. 2.6 shows the generalized form of power system stabilizer. Some common stabilizer input signals V_{SI} are: accelerating power, speed, frequency and terminal voltage. Provision for modeling of high frequency (greater than 3 Hz) filters, which may be needed for some input signals is incorporated by constants, A_1 through A_6. The next blocks allow two stages of lead-lag compensation. Stabilizer gain is set by the term K_S and signal washout is set by the time constant T_5. The stabilizer output V_S is added to the terminal voltage error signal at the location shown in fig. 2.5a.

The power system stabilizer has not been used in the present study.

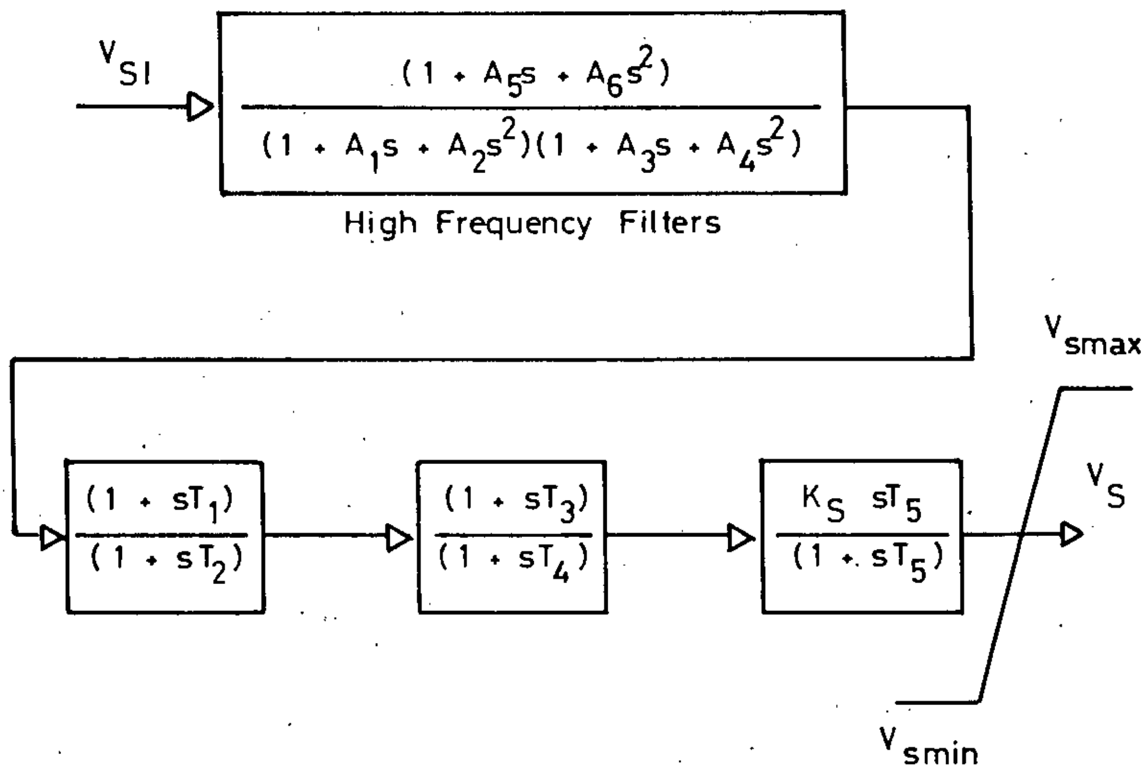


Fig.2.6 Power System Stabilizer Block Diagram

2.2.7 Transmission Network Representation [41]

The transmission network modeled by lumped π representation is shown in figure 2.7. With balanced condition assumed, the state equations representing the transmission lines are given below:

For each transmission line, the equations written in the rotor reference frame are

$$v_{qt} = r_e i_{ql} + \frac{x_e}{\omega_e} D i_{ql} + \frac{\omega}{\omega_e} x_e i_{dl} + V_{qB} \qquad (2.7.1)$$

$$v_{dt} = r_e i_{dl} + \frac{x_e}{\omega_e} D i_{dl} + \frac{\omega}{\omega_e} x_e i_{ql} + V_{dB} \qquad (2.7.2)$$

where

$V_{qB} = V_{RB} \cos \delta$

$V_{dB} = V_{RB} \sin \delta$

V_{RB} is the voltage magnitude of the chosen reference bus, v_{dt} and v_{qt} are the direct and quadrature axis components of the terminal voltage, r_e and x_e are shown in fig. 2.7.

2.2.8 Load Representation

Various load representations are used for stability studies. Constant impedance, constant current or constant power and constant power factor load models may be used. Constant impedance representation is common because of the constant impedance elements lend themselves to simple models in which case loads may be included in the admittance matrix of the system and it is possible to achieve a completely closed form simulation algorithm by making the assumption that all loads have a constant impedance current-voltage-frequency characteristic which saves computational time and effort.

From the above consideration, the simplest type of load representation, constant impedance, is used throughout the study. The load is described by the complex matrix equation

$$[V] = [Z] [I] \qquad (2.8)$$

or by its inverse

$$[I] = [Y] [V] \qquad (2.9)$$

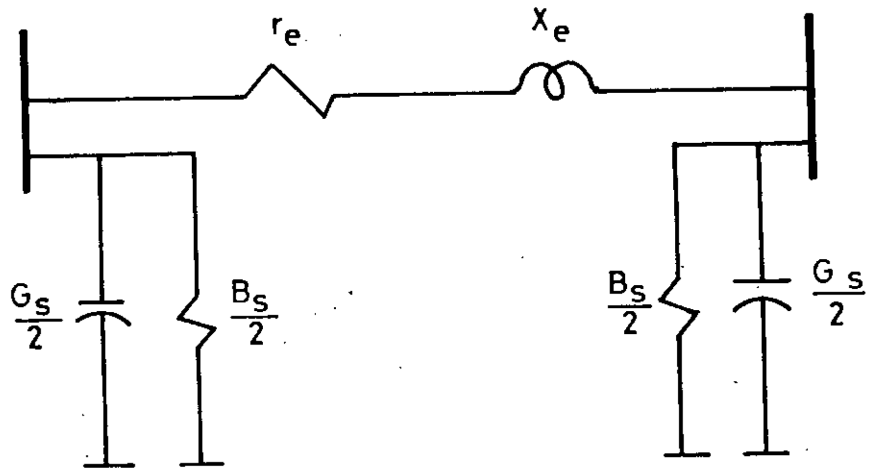


Fig. 2.7 Transmission Line π -Representation

2.3 DYNAMIC MODEL OF A SINGLE MACHINE INFINITE BUS SYSTEM [41]

A single machine is connected at its terminals to a very large power system, a system so large that the voltage at the terminals of the generator will not be altered by any changes in the excitation of the generator. The bus to which the generator is connected is sometimes called an infinite bus, which means that its voltage will remain constant and no frequency change will occur regardless of changes made in power input or field excitation of the synchronous machine connected to it. More precisely, a major bus of a power system of very large capacity compared to the rating of the machine under consideration is approximately an infinite bus.

Consider a power system consisting of one machine connected to infinite bus through transmission line as in figure 2.8(a). The equation of motion of the rotor is given by the swing equation (2.6). To obtain a solution for the rotor angle, we need to develop expression for the mechanical and electrical powers. In this section the simplest mathematical model is used. For this purpose we require the following assumptions:

1. The synchronous machine is modeled by a constant voltage behind its transient reactance.

2. The mechanical input remains constant during the period of the transient.

3. The damping constant of the machine is assumed to be negligible.

4. The mechanical angle of the synchronous machine rotor coincides with the electrical phase angle of the voltage behind transient reactance.

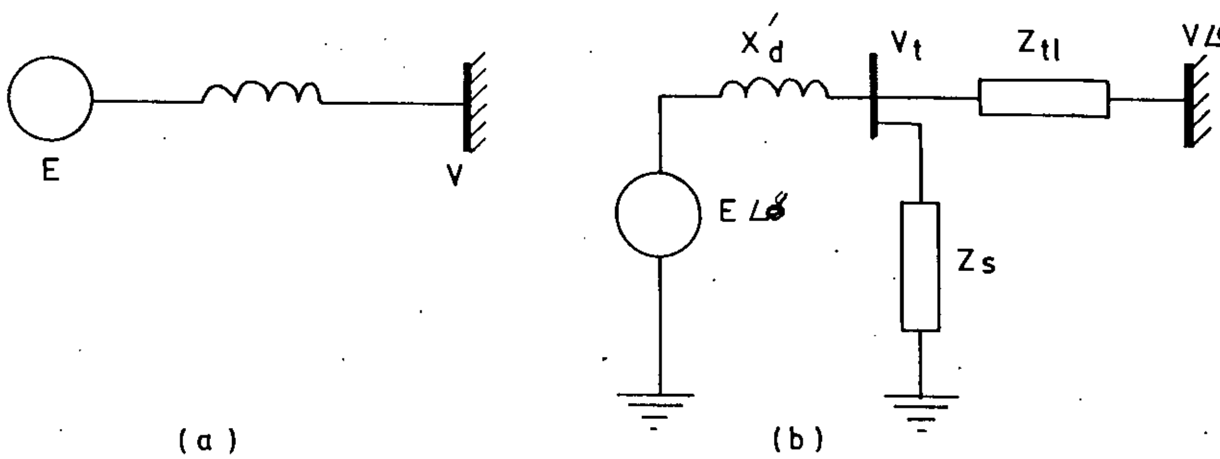


Fig. 2.8 Single machine infinite bus system : (a) Single line diagram
(b) Equivalent circuit.

5. Variation of the line admittance and the generator inertia constant due to frequency perturbations are ignored.

6. If a local load is fed at the terminal voltage of the machine, it can be represented by a constant impedance (or admittance) to neutral.

The above assumptions lead the representation of the single machine infinite bus system by swing equation only.

The equivalent electrical circuit for the system is given in figure 2.8(b). In figure 2.8,

V_t	=	terminal voltage of the synchronous machine
V	=	voltage of the infinite bus, which is used as reference
Z_{tl}	=	series impedance of the transmission line
Z_s	=	equivalent shunt impedance at the machine terminal, including local loads only.

By using Y-Δ transformation, the node representing the terminal voltage V_t in figure 2.8 can be eliminated. The transformation is shown in figure 2.9. Note that while three admittance elements are obtained (y_{12}, y_{10} and y_{20}), y_{20} is omitted since it is not needed in the analysis. The two port network of figure 2.9 is conveniently described by the equation

$$\begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \end{bmatrix} = \begin{bmatrix} \bar{Y}_{11} & \bar{Y}_{12} \\ \bar{Y}_{21} & \bar{Y}_{22} \end{bmatrix} \begin{bmatrix} \bar{E} \\ \bar{V} \end{bmatrix} \quad (2.10)$$

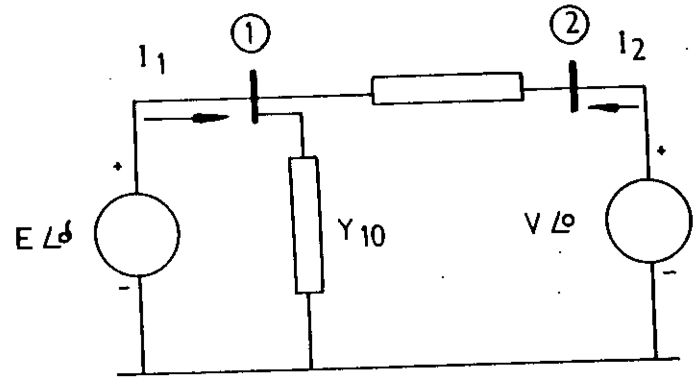


Fig. 2.9 Equivalent single machine system

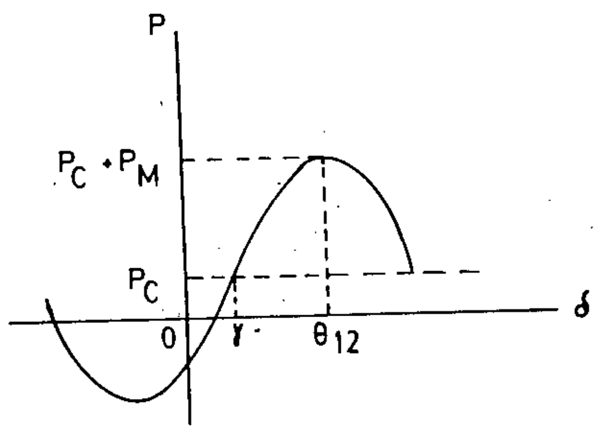


Fig. 2.10 Power angle diagram

At node 1, for figure 2.9,

$$\bar{Y}_{11} = Y_{11} \angle\theta_{11} = \bar{y}_{12} + \bar{y}_{10}$$

and $Y_{12} = Y_{12} \angle\theta_{12} = -\bar{y}_{12}$

Then the power at node 1 is given by

$$P_1 = \text{Re}\ [\ \bar{E}\bar{I}_1^*\ ]$$

$$= E^2 Y_{11} \cos\theta_{11} + EVY_{12} \cos(\theta_{12} - \delta) \qquad (2.11)$$

Now define $G_{11} = Y_{11} \cos\theta_{11}$ and $\gamma = \theta_{12} - \pi/2$, then the expression for electrical power output can be written as

$$P_1 = E^2 G_{11} + EVY_{12} \sin(\delta - \gamma)$$

$$= P_c + P_m \sin(\delta - \gamma) \qquad (2.12)$$

The relation between P_1 and δ in (2.12) is shown in figure (2.10).

The quantity P_c represents the power dissipation in the equivalent network. In the special case where the shunt load at the machine terminal V_t is open and where the transmission network is reactive, then $P_c = 0$ and $\gamma = 0$.

2.4 DYNAMIC MODEL FOR MULTIMACHINE POWER SYSTEM [41]

The complete model of power system is obtained by representing all the components, viz machine, exciter, turbine-governor, transmission line and loads, together. The state space representation can be written as

$$D\dot{X} = f(X,u,t) \qquad (2.13)$$

where X is the state vector, and u is the control vector.

The simplified mathematical model which adequately describes the non-linear dominant dynamic behavior of a multi-machine system is realized by imposing the following physical assumptions:

1. Each electrical machine is represented as a constant voltage behind transient reactance.
2. The governor-turbine time constants are assumed larger than the transient swing period; hence the mechanical power input is taken to be constant.
3. Damping or asynchronous power is negligible.
4. The mechanical angle of a machine coincides with the angle of the voltage behind the transient reactance.
5. The interacting network is assumed to be linear and loads are represented by constant admittances to permit eliminations of all nonlinear nodes (buses).

Because of above assumptions each machine is represented by the swing equation only.

The admittance matrix is defined by

$$\bar{I} = \bar{Y}\,\bar{E} \qquad (2.14)$$

where $\bar{Y}$ has the diagonal elements $\bar{Y}_{ii}$ and the off-diagonal elements $\bar{Y}_{ij}$.

Then the explicit equation for the power output of the i-th machine can be given as [44]

$$P_{ei}(\delta,t) = E_i^2\, G_{ii} + \sum_{\substack{j=1 \\ \neq i}}^{n} E_i E_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (2.15)$$

$$i = 1,2 \;\ldots\ldots\; n$$

where

E_i = voltage behind transient reactance of machine i

$Y_{ij}\angle\theta_{ij}$ = transfer admittance between machines i and j

$Y_{ii}\angle\theta_{ii}$ = driving point admittance for node i

$= G_{ii} + j\,B_{ii}$

CHAPTER 3

STABILITY ANALYSIS USING DYNAMIC BRAKE & EXCITATION CONTROL

3.1 INTRODUCTION

In this study, switchable dynamic braking resistor has been used as a means of fast load injection and electrical thrust actions typified by shunt reactor switching whereas excitation control scheme has been designed for subsequent small swings. The shunt reactor essentially modify the energy flow levels within the system with negligible energy absorption. The effectiveness of the scheme depends on the availability of the dynamic brake in sufficient dose to absorb the transient energy. Excitation control using signals derived from rotor shaft speed deviation, acceleration, torque angle variation etc. have been found to improve dynamic stability. In this chapter, one machine infinite bus system is used to show the suitability of the dynamic brake and switching reactor and excitation system for transient stability augmentation.

3.2 ANALYSIS USING DYNAMIC BRAKE & SHUNT REACTOR

A dynamic brake is a resistor with very high power dissipation capacity (in the order of 1000 MW or more) for short time periods (fraction of second) which may be switched on and off at a bus in a power transmission network, during the course of transient period to dissipate the otherwise destabilizing energy. The location of a brake is most likely to be at or near a generating station to prevent loss of synchronism during a transient by dissipating the accelerating energy.

A generator decelerates when the electrical output power is more than the mechanical input. In this situation if the electrical output of the machine is reduced by some means it can be accelerated. This is done by inserting a shunt reactor at the terminal of a decelerating machine. The shunt reactor switching acts opposite to brake injection. It reduces the electrical output power of the generator.

3.2.1 Formulation of the Problem

Figure 3.1 describes the system configuration of a single machine infinite bus system with a dynamic braking resistor and a shunt reactor at the high tension side of the generator transformer. The machine is represented by a constant voltage E behind the direct axis transient reactance x_d.

Assumptions

The following simplifying assumptions are made:

1. Three-phase symmetry is assumed for loads and faults.
2. The generator is modeled by a constant voltage behind its transient reactance,
3. Line resistance is assumed negligible.
4. The governor-turbine time constants are assumed larger than the transient swing period; hence the turbine power is to be constant during the brake operation.
5. Variations of the line admittance and the generator inertia constant due to frequency perturbations are ignored.
6. The damping constant of the machine is assumed to be negligible.
7. The generator bus voltage is assumed to be kept constant.
8. In the event of a fault the brake action starts only after the fault is cleared or some of several parallel

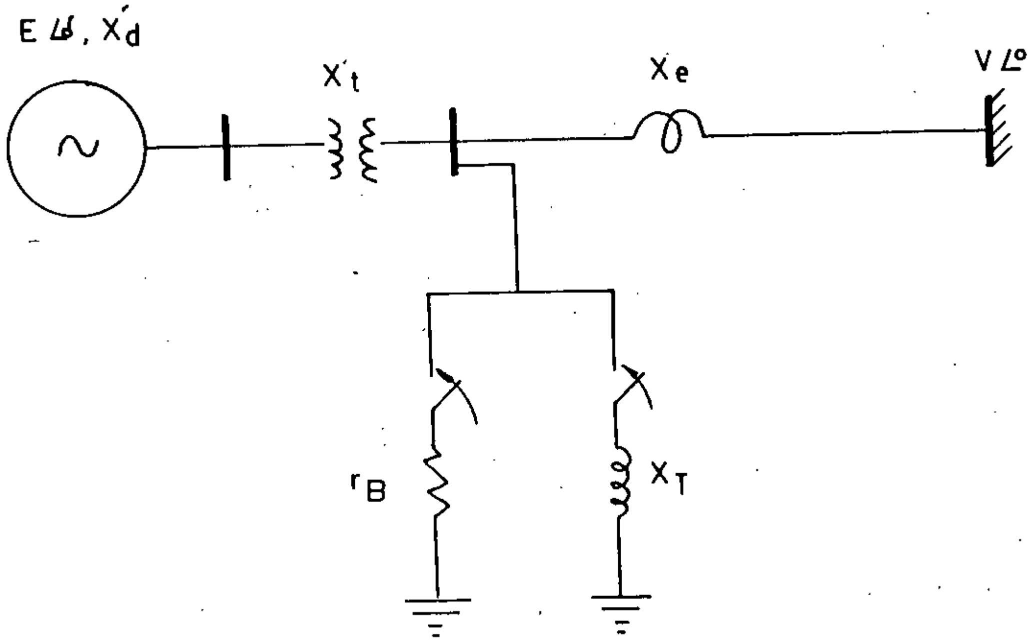


Fig. 3.1 Single machine infinite bus system:
With braking ragistor and shunt reactor

lines are out. The parameters of the system under consideration thus correspond to the post-fault topology.

9. A post-fault steady-state operating point is assumed feasible with these parameters.

10. Any load on the generator bus is assumed constant.

The generalized power flow of the electrical machine has been derived on the assumption that all the locally available fast control means (i.e. dynamic brake r_b, shunt reactor X_T) activated simultaneously. Following this procedure the real power output of the machine is given by (also shown in section 2.3)

$$P_e = EVY_T \sin(\delta - \gamma) + V_m^2 G_b \qquad (3.1)$$

where

V_m = Voltage at the terminal of the brake

$$G_b = \frac{1}{r_b}$$

Y = the transfer admittance between the machine terminal and the infinite bus.

This admittance can be computed as follows:

By Y – Δ transformation, the impedance between the machine terminal and the infinite bus is given by

$$Z_T = \frac{X_s X_e + X_e \dfrac{r_b X_T}{r_b + X_T} + X_s \dfrac{r_b X_T}{r_b + X_T}}{\dfrac{r_b X_T}{r_b + X_T}}$$

$$Z_T = \frac{X_s X_e (r_b + X_T)}{r_b X_T} + X_e + X_s \qquad (3.2)$$

Define the parameters B_s, B_e, B_T as reciprocals of X_s, X_e, X_T respectively and $X_s = X_d' + X_t$, where X_t is the reactance of the transformer.

Now equation (3.2) can be written as

$$Z_T = \frac{(B_T + G_b)}{B_s B_e} + \frac{B_s + B_e}{B_s B_e} = \frac{B_T + G_b + B_s + B_e}{B_s B_e}$$

The reciprocal of Z_T is

$$Y = \frac{B_s B_e}{B_T + G_b + B_s + B_e} = \frac{B_s B_e}{G_b + B} \qquad (3.3)$$

where $B = B_T + B_s + B_e$.

Define magnitude of Y and Y_T and is given by

$$Y_T = \frac{B_s B_e}{\sqrt{G_b^2 + B^2}} \qquad (3.4)$$

and

$$\gamma = \tan^{-1}\left(\frac{B}{G_b}\right) - \frac{\pi}{2}$$

3.2.2 Analysis of Braking Resistor Switching

To investigate the effect of switching of a given size of dynamic braking resistor on the machine terminal substitute $B_T = 0$ in equation (3.1). In this case the electrical power output can be written as

$$P_e = P_{max} \sin(\delta - \gamma_r) + V_m^2 G_b \qquad (3.5)$$

where

$$P_{max} = YEV$$

$$Y = \frac{B_s B_e}{\sqrt{G^2_b + B^2_g}}$$

$$\gamma_r = \tan^{-1}\frac{B_g}{G_b} - \frac{\pi}{2}$$

$$B_g = B_e + B_s$$

From equation (3.5) the effect of the dynamic brake can easily be deduced. The principal effect is reflected in the second term of equation (3.5). This quantity represents the power absorbed in the braking resistor.

This can be seen as a temporarily injected local load at the machine terminal. In addition, the equivalent transfer admittance Y is also affected. If the effect on Y were not present, one can view the effect of dynamic braking resistor as an additive power control available on the shaft of the machine. The effect on Y can be minimized but not eliminated by choosing the dynamic braking resistor sufficiently large to meet the locally desired transient stability margin improvement in case of multimachine system.

3.2.3 Choice of Dynamic Braking Resistor

Equation (3.5) essentially describes the machine output power. This equation can be used to study the variation of electrical power output with the variation of the braking resistor values. Figure 3.2 describes a family of power versus rotor angle curves with corresponding value of G_b. From these curves we can predict a suitable value of braking resistor which gives sufficiently large power output compared to the output without braking resistor. The switching of particular value of braking resistor constitutes an effective antidote to an advancing machine on severe system fault. Therefore, braking resistor can effectively be used for transient stability augmentation through a well structured control logic.

3.2.4 Analysis of Shunt Reactor Switching

To see the effect mathematically substitute $G_b=0$ in equation (3.1), which gives the power output of the machine in case of shunt reactor switching. The electrical output is given by

$$P_{es} = P_{max} \sin \delta \qquad (3.6)$$

where

$$P_{max} = EV \frac{B_s B_e}{B_T + B_e + B_s}$$

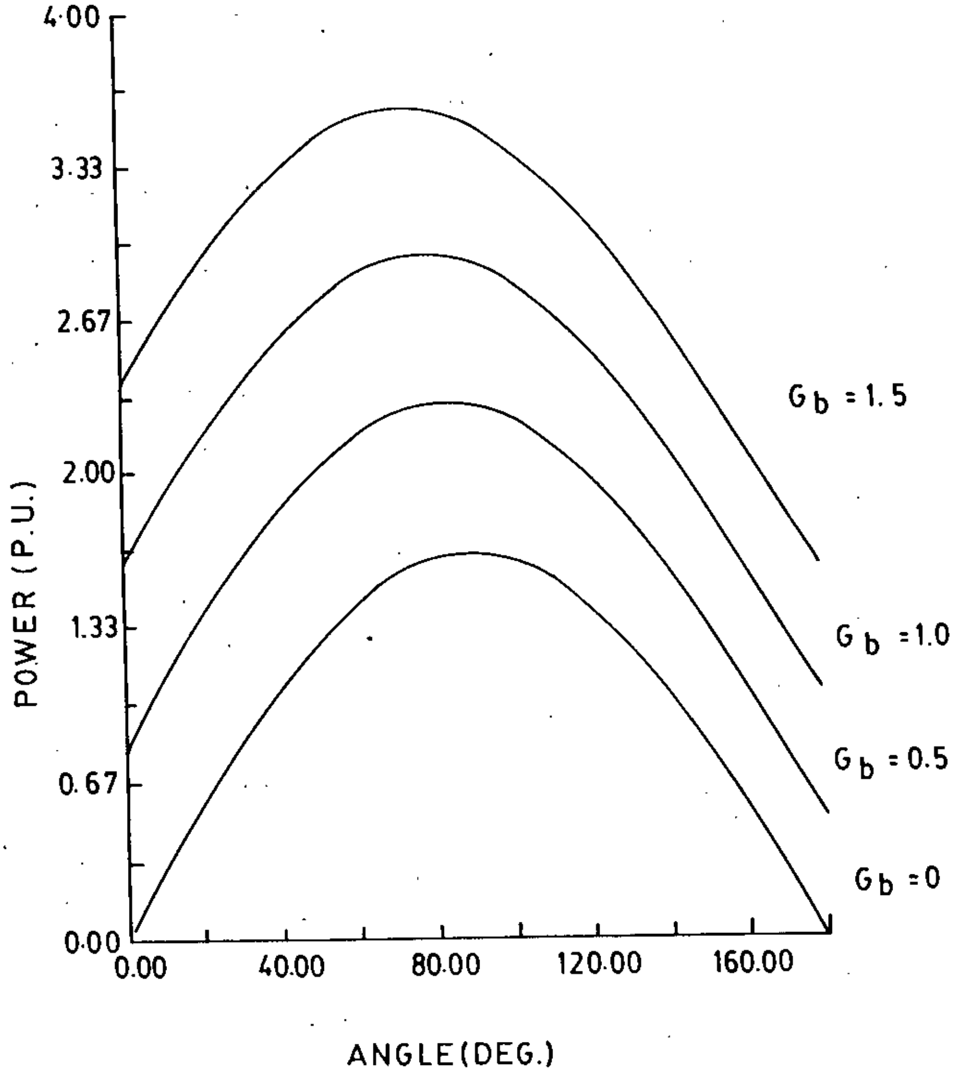


Fig. 3.2 A Family of Power Versus Rotor Angle Curves for Various of G_b

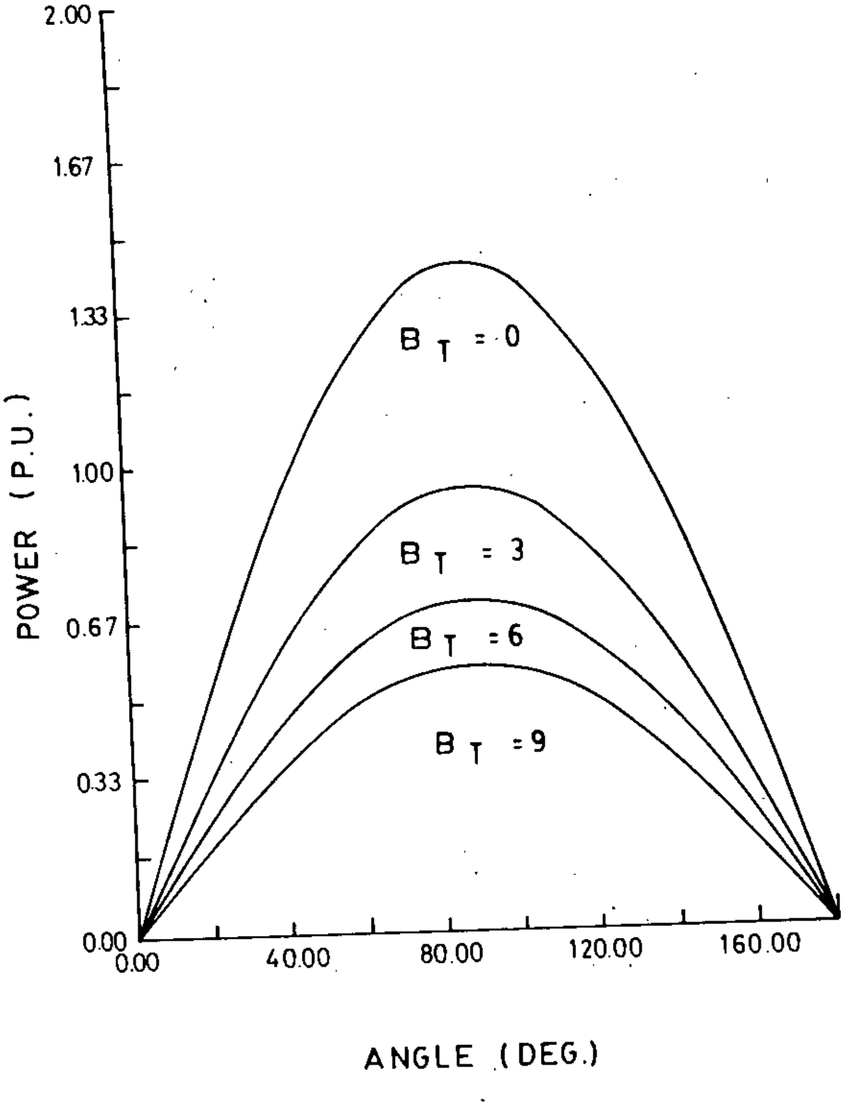


Fig. 3.3 A Family of power versus rotor angle curves for various values of X_T

Figure 3.3 illustrate the variation of the electrical output with variation of the size of the shunt reactor. It is apparent that the effect of the shunt reactor is the electrical unloading of the machine. So using an well structured control logic shunt reactor can be used for temporary load shedding.

3.2.5 Choice of Shunt Reactor Size

A sudden reduction in the maximum transferable power due to shunt reactor switching will accelerate the machine. Because in this case the mechanical input power will be more than the electrical output. In the simplified single machine infinite bus system this condition may be fulfilled if in the choice of shunt reactor size the following relation holds.

$$\Psi_T \, P_{max} = EV \frac{B_s B_e}{B_T + B_s + B_e} \qquad (3.7)$$

Here Ψ_T is a constant to be chosen such that $0 \leqslant \Psi_T \leqslant 1$. $\Psi_T = 0$ represents the minimum of all feasible value of the shunt reactor. This condition is excluded to avoid intentional short circuit [15]. Rearranging equation (3.7), B_T is obtained as

$$B_T = [\, B_s B_e EV - \Psi_T \, P_{max} \, (B_s + B_e)/\Psi_T \, P_{max} \qquad (3.8)$$

It is assumed that every parameter on the right hand side of equation (3.8) is known. Thus the selection of shunt reactor based on the criterion guarantees that the mechanical input is always greater than the electrical output for the simple system under consideration. It is evident that the specific value of the shunt reactor is a function of the system parameters and loading condition.

3.3 ANALYSIS USING EXCITATION CONTROL

After improvement of transient stability or first swing stability by using dynamic brake and shunt reactor, efforts have been made to stabilize the subsequent swing or dynamic instability employing excitation control. Dynamic brakes are concerned with large power variation during transient stability that it is almost impossible to handle this power with excitation control. The power handling capacity of excitation control is very low to use it to improve transient stability. Modern fast excitation systems are usually acknowledged to be beneficial to dynamic stability involving smaller disturbance. With proper design and compensation, fast acting, high-gain excitation systems exert a considerable influence upon power system stability of subsequent swings following the first swing.

3.3.1 Effect Of Exciter On Subsequent Swings

The oscillations after the first swing are relatively small but they are not allowed to continue because these oscillations exist for a long time. Even various modes of oscillations reinforce each other during later swing which along with the inherent weak system damping can cause instability though the first swing is improved by braking. The effect of excitation compensation on subsequent swings is very pronounced.

3.3.2 Principle of Operation of Exciter During Subsequent Swings

In dynamic stability, the machine is subjected to small oscillations of large duration and causes a reduction in machine terminal voltage and in the ability to transfer synchronizing power. Considering a single machine infinite-bus system, output power is given by [see equation (1.1)]

$$P_o = \frac{V_t V}{X} \sin \delta \qquad (3.9)$$

where

V_t is terminal voltage of the machine and V is the infinite bus voltage.

If V_t is reduced, P_0 is reduced proportionally. To prevent this reduction in P_0 requires very fast action by the excitation system. Forcing the field voltage to increase thereby increasing internal voltage and terminal voltage reasonably. From the view point of field flux, during smaller disturbance, the armature reaction tends to decrease the flux linkage linking the main field winding. The voltage regulator tends to force the excitation system to boost the flux level. Thus if a control signal is provided corresponding to the change in terminal voltage to exciter, voltage build up or build down is easily performed and considerable effect on dynamic stability results.

3.3.3 Operation of Excitation System

The IEEE type I Excitation system model is already described in chapter 2. Now the operation of such a system is described in some detail.

A new detailed block diagram is shown in figure 3.4. The regulator couples the variables of the synchronous machine to the input of the exciter through feedback and forward controlling elements for the purpose of regulating the synchronous machine output variables. Thus the regulator controls the output of the exciter (E_{fd}) so that the internal voltage of the machine changes in desired way.

In modern system, the excitation is supplied directly from on SCR with an alternator source. Hence it is only necessary to adjust the SCR firing angle to change the excitation level and this involves essentially no time delay. A range of exciter ceiling voltage upto 8 per unit may be obtained for the modern electronic exciter.

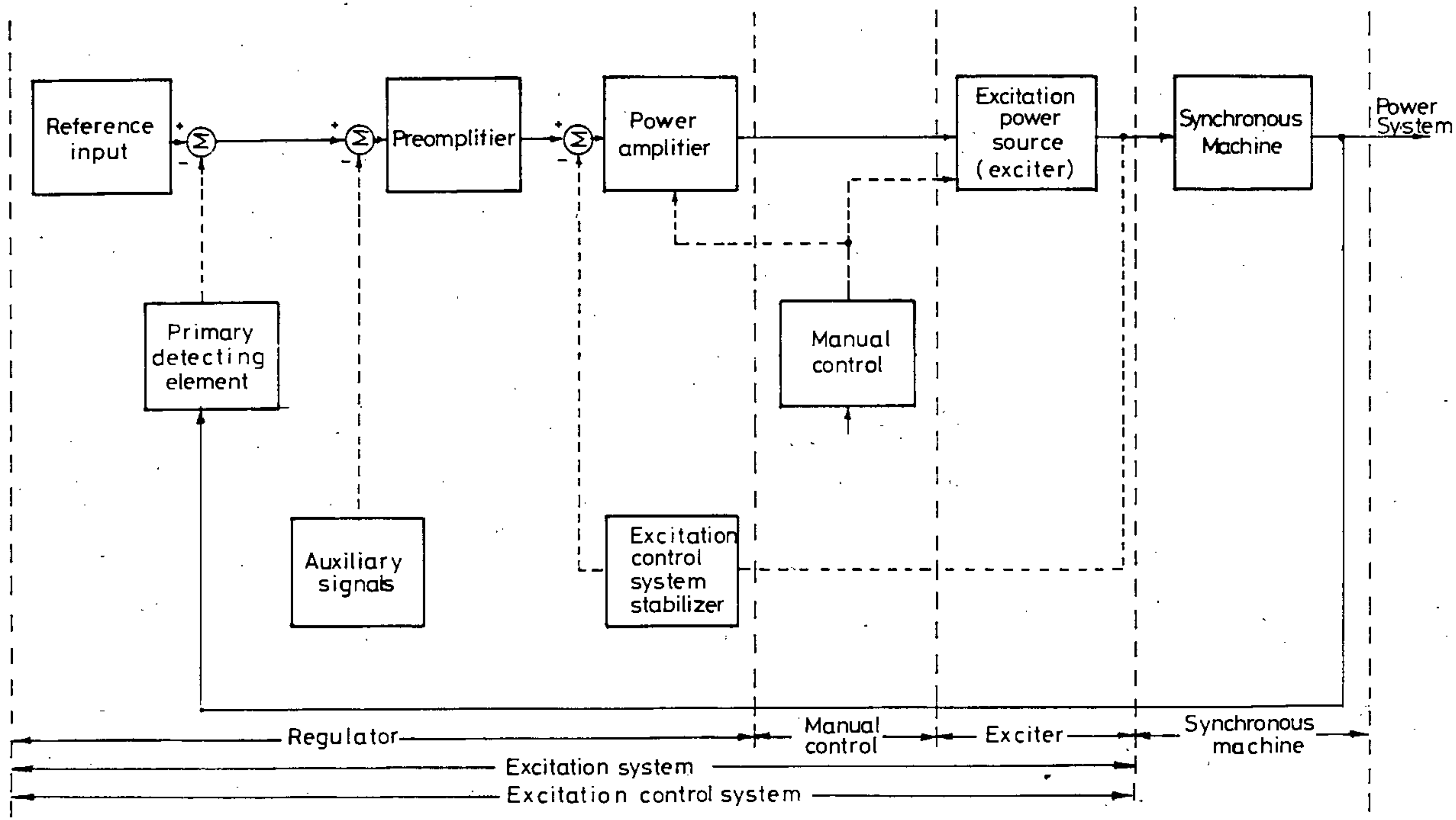


Fig. 3.4 EXCITATION CONTROL SYSTEM

Inherent adverse effects of high gain excitation system make it necessary to use auxiliary stabilizing signals in addition to normal automatic voltage regulation. The fast response and high ceiling available from modern static excitation system, when activated by stabilizing signals improve stability. A fixed load time control of the braking resistor improve transient stability and the stabilizing input signals act on the exciter in such a direction to create greater stability for subsequent swings. The following possible stabilizing signals have been considered [21]:

1. rate of change of terminal voltage, V_t
2. speed error, $\Delta\omega$
3. acceleration, $D\omega$
4. rate of change of field current, ΔI_{fd}
5. transient direct axis field current, $\Delta i'_{fd}$
6. transient quadrature axis field current, Δi_{fq}
7. rate of change of armature current
8. relative rotor angle deviation, $\Delta\delta$.

These stabilizing signals through the action of regulator changes output of the exciter (E_{fd}). So the control for the study is exciter output voltage and the control is obtained directly as a function of stabilizing signals. In our study, the stabilizing signals are derived from rotor shaft speed deviation, acceleration and torque angle variation. These signals are introduced as auxiliary signals employed in the summer just before the preamplifier in figure 3.4.

CHAPTER 4

MATHEMATICAL DEVELOPMENT FOR A QUASI-OPTIMAL CONTROL STRATEGY

4.1 INTRODUCTION

The phenomena of stability of synchronous machine for the mode of transient and dynamic stability can be improved by dynamic braking-shunt reactor and excitation control means respectively discussed in the previous chapter. Concurrent with these are improvements in calculating methods, switching strategy and working capability making it feasible for online computation. The strategy has to be such as to control the transients in the best or 'optimal' manner maintaining stability.

Numerous procedures for the control of power system stability based on modern control theory have been proposed. These schemes have not been enthusiatically received by power system engineers because of the amount of online computation, the real time measurement, telemetering problems and complexity of the system involved. These procedures have limited universal applicability. Typically these schemes are open loop in structure and the magnitude and duration of control action are a predetermined compromise based on various possible contingencies. This situation can obviously result in harsh overcontrol for relatively mild contingencies and inadequate control for the severest contingencies. Localized aim strategies provide feedback-control schemes requiring very little online computation and simple local measurements.

The disturbances appearing in a power system are, in general, not known in advance. This implies that an apriori determined control strategy may not be suitable or even may not be appropriate. This suggests that in order for the control to be effective any optimal strategy must be found in closed loop and also expressed in terms of variables which are easily accessible. Development of such a scheme with simulation results are presented in the following sections.

The control problem can be formulated into a minimum time control problem based on Pontryagin's minimum principle. In this chapter Pontryagin's minimum principle is used to develop an "optimal" control based on a reasonably specified criterion. A "quasi-optimal" closed loop scheme is then accordingly presented and used in carrying out computer simulation tests.

4.2 MODEL FOR SINGLE MACHINE USING DYNAMIC BRAKE AND REACTOR CONTROL

The braking resistor and shunt reactor control strategy has been developed first for a simple system - a single generator feeding an infinite bus. The solution then may be generalized to a network of multimachine equipped with many brakes.

4.2.1 System Configuration

The single generator under study is connected to an infinite bus through a double circuit transmission line. The braking resistor and shunt reactor have been connected to the high tension side of the generator transformer as shown in figure 4.1.

In transient stability studies the period of interest is very short and hence the dynamics of the system can be represented approximately by the generator swing equation only, given by

$$MD^2\delta(t) + dD\delta(t) = P_m - P_e(t) - P_b(t) \qquad (4.1)$$

Here P_m, P_e, P_b are the mechanical input, electrical output power and power absorbed by the braking resistor respectively, δ is the rotor angular position, M and d are the generator inertia and damping coefficient respectively.

By switching the resistor in and out of the circuit, the power absorbed

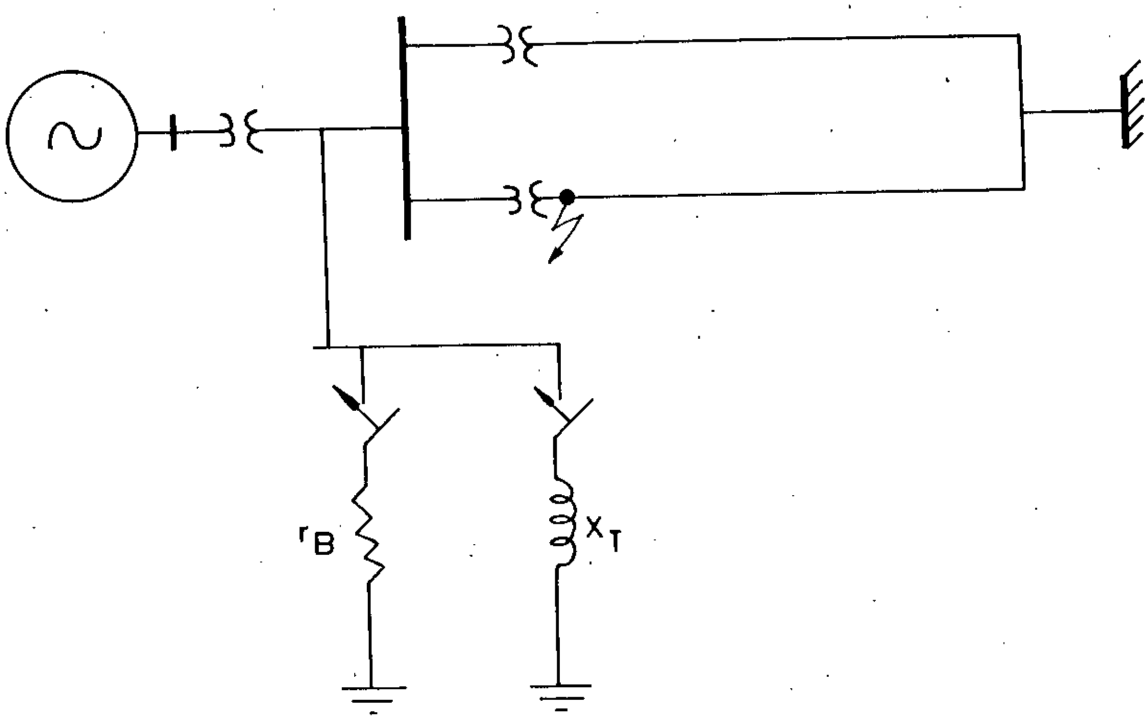


Fig. 4.1. Single machine infinite bus system for testing the proposed control algorithm

in the resistor $P_b(t)$ can be varied between maximum and zèro respectively. It is assumed that at one time either the braking resistor or shunt reactor will be switched in. Switching the resistor in is a load injection, and shunt reactor insertion amounts to reduction in power transferred (P_e) by machine.

4.2.2 Statement of the Control Problem [1,43]

Following a disturbance in the system, if the trajectory remains in the region of attraction of the equilibrium (operating) point, then the system is said to be stable. If the disturbance is large, as in the case of a severe fault or loss of large load, the trajectory may leave the boundary of the stability region. If action is not taken quickly enough to bring the trajectory back to the domain of attraction of the post-disturbance system equilibrium point, the synchronous machines will run out of step. So, the performance measure to be minimized in such problems can be selected to be "time". For normal operation of the machine, the steady state speed variation should be zero while the rotor angle will be limited between $-\pi/2$ (motor operation) and $\pi/2$ (generator operation) radians.

Assuming $\delta(t) = x_1$ and $D\delta(t) = \omega(t) = x_2$, equation (4.1) can be broken up into the following two equations

$$\frac{dx_1}{dt} = x_2$$

$$\frac{dx_2}{dt} = L(x) + bu(t) \qquad (4.2)$$

where $L(x)$ contains the accelerating power and control u is the power absorbed in the braking resistor (P_b). The damping power may be included in $L(x)$ or may be neglected since it is very small. The control u is constrained by the upper and lower bounds as follows:

$$0 \leqslant u(t) \leqslant 1 \qquad (4.3)$$

Switching the shunt reactor will reduce the output power and will be reflected in $L(x)$. The control $u(t)$ is zero under this condition.

The optimization problem then can be stated as :

Given the system described by equation (4.2), find the control $u(t)$ which minimizes the cost index [43]

$$J = \int_{t_o}^{t_f} dt \qquad (4.4)$$

and transfers the system from initial (perturbed) states to the target states (considering only generator action).

$$0 \leqslant x_1 (t_f) \leqslant \pi / 2$$
$$(4.5)$$
$$x_2 (t_f) = 0$$

at the same time satisfying the inequality constraint (4.3).

4.2.3 Derivation of the Closed-loop Control Strategy [1,43]

In general, the solution of the above mentioned minimum time problem is not simple because of the nonlinear term $L(x)$ in equation (4.2). Closed loop solution for $u(t)$, as such, is further more complicated, if at all possible. In order to arrive at a closed loop solution scheme, the following analysis is adopted:

The term $L(x)$ comprises of the machine accelerating power and is a measurable quantity. Assuming the system is controllable, the accelerating power should be less than the power absorbed in the brake, or

$$| L(x) | \leqslant bu(t) \qquad (4.6)$$

Let us assume that at time $t=t_o$, $L(x)=L_o$ is known quantity. The system equation can be written as

$$\frac{dx_1}{dt} = x_2$$

$$\frac{dx_2}{dt} = L_o + bu(t) \qquad (4.7)$$

The optimal control problem can be reformulated as follows:

Given the system

$$\frac{dx_1}{dt} = x_2$$

$$\frac{dx_2}{dt} = u_o(t), \quad u_{o\,min} \leqslant u_o(t) \leqslant u_{o\,max} \qquad (4.8)$$

where

$$u_o(t) = L_o + bu(t) \qquad (4.9)$$

Find the admissible control that forces the system (4.5) from any initial state $[x_1(0), x_2(0)]$ to

$$0 \leqslant x_1(t_f) \leqslant \pi/2 \qquad (4.10)$$

$$x_2(t_f) = 0$$

As from Appendix D, Pontryagin's minimum principle (PMP) [43] is used to find the time optimal control of the system (4.8). Using equation (D.3) of Appendix D, the Hamiltonian for (4.8) is given by

$$H = 1 + x_2(t)p_1(t) + u_o(t)p_2(t) \qquad (4.11)$$

If $x^*(t)$, $p^*(t)$ and $u_0^*(t)$ correspond to the optimal state, costate, and control respectively, then by the minimum principle, the inequality [D.4]

$$1+x^*_2(t)p^*_1(t)+u_0^*(t)p_2^*(t) \leqslant 1+x_2^*(t)p_1^*(t)+u_0(t)p_2^*(t) \quad (4.12)$$

holds for all admissible $u_0(t)$ and for $t \in [t_0, t_f]$.
Equation (4.12) gives

$$u_0^*(t) = \begin{cases} u_{0min}, & \text{if } p_2(t) > 0 \\ u_{0max}, & \text{if } p_2(t) < 0 \end{cases} \quad (4.13)$$

Assume $u_0(t) = \alpha$ (which is either u_{0min} or u_{0max}) and let $x_1(0) = \tau_1$ and $x_2(0) = \tau_2$. Equation (4.8) can be solved with these initial conditions for constant control to obtain the relations.

$$x_2(t) = \alpha t + \tau_2 \quad (4.14)$$

and

$$x_1(t) = \tau_1 + \tau_2 t + \alpha t^2/2 \quad (4.15)$$

Next eliminating t by substituting $t = \frac{x_2 - \tau_2}{\alpha}$ form equation (4.14) into (4.15), gives

$$x_1(t) = \tau_1 + \frac{x_2^2}{2\alpha} - \frac{\tau_2^2}{2\alpha} \quad (4.16)$$

The trajectories passing through ($x_1 = 0$, $x_2 = 0$) and ($x_1 = \pi/2$, $x_2 = 0$) are given by the following equations.

$$x_1(t) = \frac{x_2^2}{2\alpha} \quad (4.17)$$

$$x_1(t) = \frac{\pi}{2} + \frac{x_2^2}{2\alpha} \quad (4.18)$$

The control law can then be given as

$$u^*_o(t) = \begin{cases} u_{o\,min}, & (x_1, x_2) \in R_1 \\ \\ u_{o\,max}, & (x_1, x_2) \in R_2 \end{cases} \qquad (4.19)$$

In terms of u(t) the control law is given by

$$u^*(t) = \begin{cases} 1, & (x_1, x_2) \in R_1 \\ \\ 0, & (x_1, x_2) \in R_2 \end{cases} \qquad (4.20)$$

Regions R_1 and R_2 are divided by the switch curve Σ (the switch curve is the locus of all points (x_1, x_2) which can be forced to the terminal states by control $u_o = \alpha$) given us

$$\Sigma_o = \gamma_1^o \cup \gamma_2 \cup \gamma_3^o \qquad (4.21)$$

$$\gamma_1^o \quad : \quad x_1 - \frac{x_2^2}{2[L_o - b\,\text{sgn}\,(x_2)]} = 0, \; x_2 > 0$$

$$\gamma_2 \quad : \quad 0 \leqslant x_1 \leqslant \pi/2 \;, \quad x_2 = 0$$

$$\gamma_3 \quad : \quad x_1 - \frac{x_2^2}{2[L_o - b\text{sgn}\,(x_2)]} - \pi/2 = 0, \; x_2 < 0$$

Because of the oscillatory nature of the system, the states will not continue on the switch curve and hence this possibility is not included in (4.20). For any state in R_1, expression (4.18) will give a value of $\Sigma > 0$.

Once the control is found at t = to, this is applied for a period Δt and at $t = t_1$, the quantity L(x) is checked. If at this time it assumes a value

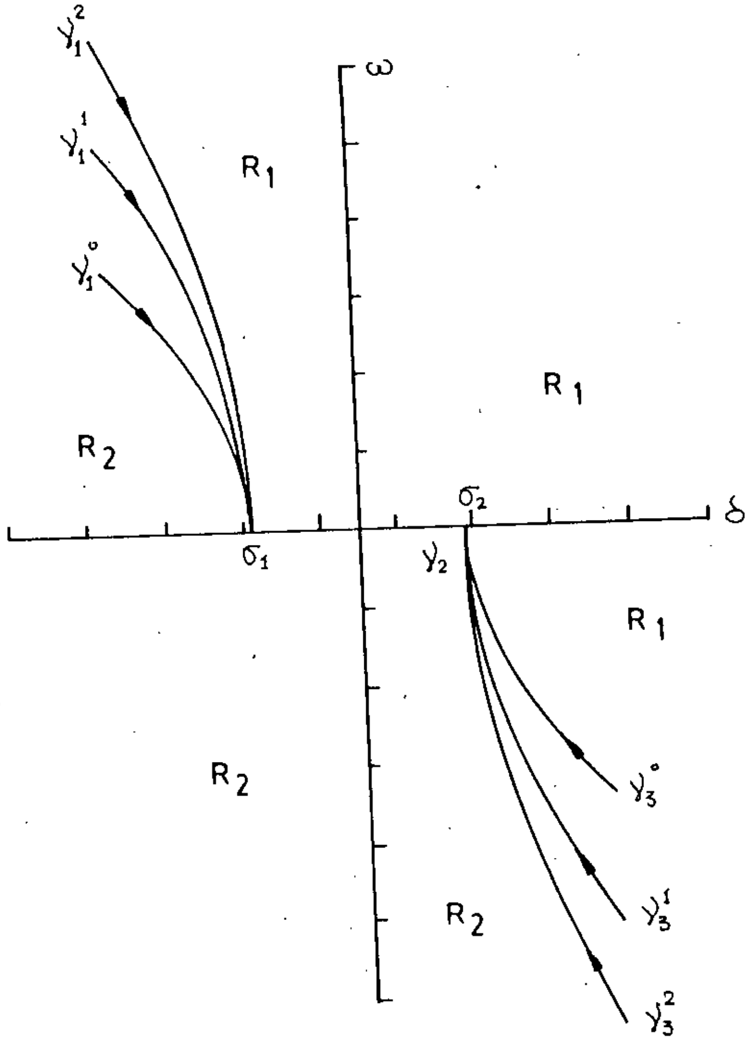


Fig. 4.2. Moving switching curves

L_1, the control decision at $t=t_1$ is made by the switch curve Σ_1, given by

$$\Sigma_1 = \gamma_1^1 \cup \gamma_2 \cup \gamma_3^1 \qquad (4.22)$$

which is evaluated the same way as (4.18) except that L_0 ia replaced by L_1. This can be generalized to find the control at any time $t=t_s$ by evaluating L(x) at that instant.

The process is repeated until the trajectory reaches sufficiently close to the target state, when it is discontinued. The control strategy is determined from a set of moving switch curves, which are shown in figure 4.2. Here an arbitrary target state set between limits σ_1 and σ_2 on the x_1 axis has been shown. Note that L(x) is a measure of the accelerating power which we have assumed smaller than the brake power. This limits the region covered by the moving switch curves.

It has to be made sure that there is no rapid switching back and forth of the control, because of sudden changes in L(x), in the area where the moving curves lie. Provision of a deadzone can take care of this. It should be selected such that there is no control action when the states are sufficiently close to the switch curves or the target set. The strategy (4.20) and (4.21) implies that if the trajectory is to the right of the switch curve ($\Sigma>0$) apply the braking resistor otherwise switch the reactor. If the states are in the deadzone $|\Sigma| \leq \varepsilon$, there will be no control action.

Computation of the control involves the following steps in finding the control

1. Determine x_1 and x_2

2. Determine $u_{s\,min}$ and $u_{s\,max}$ at $t=t_s$

3. Calculate Σ as follows

$$\text{if } x_2 > 0, \quad \Sigma = x_1 - \frac{x_2^{\,2}}{2u_{s\,max}}$$

$$\text{if } x_2 < 0, \quad \Sigma = x_1 - \frac{x_2^{\,2}}{2u_{s\,min}} - \frac{\pi}{2}$$

4. If $\Sigma > 0$: Brake applied

   If $\Sigma < 0$: Shunt reactor applied, brake off.

4.3 MODEL FOR MULTI-MACHINE SYSTEM WITH BRAKE AND SHUNT REACTOR [1]

The objective of this section is to develop closed-loop control strategy for multi-machine system. One major objective of the study is to find a suitable control scheme for switching the resistor to suit a variety of system conditions including the following:

1. Variation in system output - A single size of braking resistor would have considerably greater effect on braking five machines than ten machines.

2. The type and location of the fault - The accelerating power for a given number of machines would vary considerably depending upon the type and location of the fault.

3. Variation in reclosing time for temporary and permanent fault.

4.3.1 System Configuration

The quasi-optimal control strategy derived in previous section can easily be extended to multi-machine system. Since in a multimachine system the angle of each machine is measured with respect to a reference machine (real or fictitious), the algorithm involves the dynamics of the reference machine.

Consider the swing equations of the i-th and the r-th (reference) machines. Neglect damping terms

$$M_i D^2 \delta_i = P_{mi} - P_{ei}(t) - P_{bi}(t) \qquad (4.23)$$

$$M_r D^2 \delta_r = P_{mr} - P_{er}(t) - P_{br}(t) \qquad (4.24)$$

Divide the right hand sides by corresponding inertia constants and subtract to get

$$D^2 \delta_{ir} = M_i^{-1} [P_{mi} - P_{ei}(t)] - M_r^{-1} [P_{mr} - P_{er}(t)] - M_i^{-1} P_{bi}(t) + M_r^{-1} P_{br}(t) \qquad (4.25)$$

where

$$\delta_{ir} = \delta_i - \delta_r$$

4.3.2 Derivation of Control Strategy

From (4.25),

$$D^2 \delta_{ir} = L_i(t) - L_r(t) - b_i u_i(t) + b_r u_r(t)$$

$$= L_{ir}(t) + b^T u(t) \qquad (4.26)$$

where,

$L_{ir}(t) = L_i(t) - L_r(t)$, $b^T = [-b_i \ b_r]^T$=transpose of $[-b_i \ b_r]$.

$u(t) = [u_i(t) \ u_r(t)]^T$

Considering $\delta_{ir} = x_1$ and $D\delta_{ir} = x_2$, equation (4.26) can be broken up into two equations similar to equation (4.2)

$$\frac{dx_1}{dt} = x_2$$

$$\frac{dx_2}{dt} = L_{ir} + b^T u(t) \qquad (4.27)$$

Here the quantity $L(x)$ is replaced by L_{ir}.

Proceeding in a similar way as previous section, the control strategy can be given as follows:

$$u^*(t) = \begin{cases} 1, & (x_1, x_2) \in R_1 \\ 0, & (x_1, x_2) \in R_2 \end{cases} \tag{4.28}$$

Regions R_1 and R_2 are divided by the switch curve Σ given as

$$\Sigma_i = \gamma_1^i \cup \gamma_2 \cup \gamma_3^i \tag{4.29}$$

$$\gamma_1^i : \quad x_1 - \frac{x_2^2}{2[L_{ir} - b\,\mathrm{sgn}(x_2)]} = 0, \; x_2 > 0$$

$$\gamma_2 : \quad 0 \leq x_1 \leq \pi/2, \quad x_2 = 0$$

$$\gamma_3^i : \quad x_1 - \frac{x_2^2}{2[L_{ir} - b\,\mathrm{sgn}(x_2)]} - \pi/2 = 0, \; x_2 < 0$$

7/3//

Normally, the reference machine is considered to be the largest machine in the system and the term $L_r(t)$ is small compared to $L_i(t)$ and hence can be neglected. If, in addition, the reference machine is not equipped with the brake, then the control scheme for each machine is exactly the same as in the single machine case already discussed requiring measurement of only local variables, in addition to the power angle of the reference machine.

4.4 MODEL FOR MULTI-MACHINE SYSTEM WITH EXCITATION CONTROL [47]

A quasi-optimal excitation control for a multimachine power system is developed. The control is obtained directly as a function of relative rotor angle, frequency and acceleration of each machine with respect to a reference machine.

4.4.1 Statement of the Control Problem

A power system network can be mathematically represented by the following set of equations:

$$\frac{dx}{dt} = f\,[X,Y,u] \qquad (4.30)$$

$$G(X,Y) = 0 \qquad (4.31)$$

Equation (4.30) includes the dynamic relationships of the generators, their exciters etc. while equation (4.31) gives the algebraic relationship of voltage and currents of the generators, system interconnection etc. X is the state vector and Y includes the other variables, u is the control vector. If all control other than the excitation system is ignored, elements of the vector u represents the excitation voltage (E_{fd}) of the various generators.

The elements of the control u are constrained by their ceiling voltages

$$u_{i\,min} \leq u_i \leq u_{i\,max} \qquad (4.32)$$

For multi-machine power system, the system will remain stable if, following a disturbance or an abnormal condition, the relative speed and acceleration of each generator, with respect to some reference machine, return, in time, to zero, while steady state relative angles do not exceed 90°. The objective is to bring the system to a stable equilibrium in the shortest possible time. The control problem then can be defined as follows:

Gives the initial values of X and Y in equation (4.30) and (4.31), find an admissible control satisfying the relationships (4.30), (4.31) and (4.32), which will bring the relative velocity, acceleration to zero and angle to the desired final values ($0 - \pi/2$) and which minimizes the objective function

$$J = \int_{t_0}^{t_f} dt \tag{4.33}$$

As mentioned in previous section, that a closed-loop solution of the above stated control problem is not possible because of the complexity of the system equations. The following procedure outlines the steps involved in finding a quasi-optimal feedback control.

4.4.2 Derivation of the Closed-Loop Strategy

A control strategy is first obtained for each generator with respect to a reference machine. Obviously, the subsequent swings after the first swing is a small disturbance case where the constraint on δ is not violated. For this case, the torque equation is differentiated and control is determined from a 2nd-order model. The following model development may be obtained in details from [47].

The electromechanical swing equations can be represented by two first order differential equations as follows [47]

$$\frac{d\delta}{dt} = \omega_b n$$

$$\frac{dn}{dt} = \frac{T_i}{T_m} - \frac{T_e}{T_m} \tag{4.34}$$

Where T_i, T_e and T_m are the input torque, airgap torque and inertia constant of the generator respectively, n is the per unit angular frequency deviation and expressed as

$$n = \frac{\omega - \omega_b}{\omega_b} \tag{4.35}$$

Ignoring armature copper loss, the airgap torque can be expressed as

$$T_e = v_d i_d + v_q i_q \tag{4.36}$$

From equation (2.4) and (2.5),

$$\frac{dE_q'}{dt} = \frac{E_{fd} - E_i}{T_{do}'}$$
$$\frac{dE_d'}{dt} = -\frac{E_d'}{T_{qo}} \tag{4.37}$$

Differentiating of equation (A.8) in appendix A and substitution of equation (4.37) in it gives

$$Dv_d = x_q' Di_q - E_d/T_{qo}'$$
$$Dv_q = -x_d' Di_d + [E_{fd} - E_i]/T_{do}' \tag{4.38}$$

From the condition $D\Psi_d = D\Psi_q = 0$ and differentiation of (A.3.2) and (A.3.3) using (A.2) and (A.5), the following two equations are obtained

$$Di_d = \frac{1}{x_d'} DE_q' = \frac{1}{x_d' T_{do}'} [E_{fd} - E_i]$$
$$Di_q = \frac{1}{x_q'} DE_d' = \frac{-E_d}{x_q' T_{qo}'} \tag{4.39}$$

Combining equation (4.34) and (4.35), the torque equation for the k-th machine in the system can be written as

$$T_m D^2 (\delta/\omega_n) = T_i - v_d i_d - v_q i_q \tag{4.40}$$

Ignoring governor action, differentiation of both sides of this equation gives

$$T_m D^2(\delta/\omega_b) = -v_d D i_d - v_q D i_q - i_d D v_d - i_q D v_q \qquad (4.41)$$

Substituting relationships (4.38) and (4.39) in (4.41) and simplifying,

$$D^3(\delta/\omega_b) = \frac{v_d E_i}{x_d' T_{do}' T_m} + \frac{v_d E_d}{x_q' T_{qo}' T_m} + 2\frac{i_d E_d}{T_{qo}' T_m} - \frac{v_d}{x_d' T_{do}' T_m} E_{fd} \qquad (4.42)$$

Denoting L(t) and b(t) as

$$L(t) = \frac{v_d E_i}{x_d' T_{do}' T_m} + \frac{v_d E_d}{x_q' T_{qo}' T_m} + 2\frac{i_d E_d}{T_{qo}' T_m} \qquad (4.43)$$

$$b(t) = -\frac{v_d}{x_d' T_{do}' T_m} \qquad (4.44)$$

For k-th machine, equation (4.42) can be written as

$$D^3(\delta_k/\omega_b) = L_k(t) + b_k(t) E_{fdk} \qquad (4.45)$$

Similarly for reference machine (say the r-th),

$$D^3(\delta_r/\omega_b) = L_r(t) + b_r(t) E_{fdr} \qquad (4.46)$$

Subtracting equation (4.46) and (4.45), gives

$$D^3(\delta/\omega_b) = L(t) + u_1(t) = u(t) \qquad (4.47)$$

where

$$\delta = \delta_k - \delta_r$$

$$L(t) = L_k(t) - L_r(t) \qquad (4.48)$$

$$u_1(t) = b_k(t) E_{fdk} - b_r(t) E_{fdr}$$

For given values of $L(t)$ and $b(t)$ for each machine, the control $u(t)$ in (4.47) is constrained by the upper and lower bounds u_{max} and u_{min} (decided by values E_{fdmax} and E_{fdmin} for each machine) as follows

$$u_{min} \leqslant u(t) \leqslant u_{max} \qquad (4.49)$$

The control problem can then be redefined as follows:

Given a 3rd-order system represented by equation (4.47), where $L(t)$ is determined by the system equations (4.30) and (4.31) and initial values of which are given, find an admissible control $u(t)$ satisfying the constraint (4.49) that will transfer the states (δ,n,dn) to the final states given by

$$0 \leqslant \delta < \frac{\pi}{2\omega_b} \qquad (4.50)$$

$n = 0$ and $Dn = 0$

Assume that $L(t)$ and $b(t)$ are constant at their initial values L_o and b_o respectively and let $x_1 = \delta/\omega_b$ then (4.47) can be written as

$$\frac{dx_1}{dt} = x_2$$

$$\frac{dx_2}{dt} = x_3 \qquad (4.51)$$

$$\frac{dx_3}{dt} = u_o(t)$$

where $u_o(t) = L_o + b_o(t)$

$$\text{and } u_{omin} \leqslant u_o(t) \leqslant u_{omax} \qquad (4.52)$$

The optimization problem is to find the admissible control that forces the system (4.51) from any set of initial states $[x_1(0), x_2(0), x_3(0)]$ to

$$0 \leq x_1(t_f) \leq \frac{\pi}{2\omega_b}$$

$$x_2(t_f) = 0 \qquad (4.53)$$

$$x_3(t_f) = 0$$

in the shortest possible time.

From Pontryagin's minimal principle, the H minimal control for system (4.51), subject to constraint (4.52) is $u_{o\,max}$ and $u_{o\,min}$ depending on another switching function Σ_t. Assume that $u_{o\,max} = u_{o\,min} = \sigma$, then solving for the three equations in (4.49) and eliminating t, we will obtain

$$x_1 + \frac{1}{3\sigma^2} x_3^3 - \frac{x_2 x_3}{\sigma} = x_1(0) + \frac{1}{3\sigma^2} x_3^3(0) - \frac{x_2(0) x_3(0)}{\sigma} \qquad (4.54)$$

The equation of the surfaces passing through $[\frac{\pi}{2\omega_b}, 0, 0]$ and $[0,0,0]$ forms two switching boundaries given as

$$\Sigma_1 = x_1 - \frac{\pi}{2\omega_b} - \frac{x_2 x_3}{\sigma} + \frac{1}{3\sigma^2} x_3^3$$

$$\qquad (4.55)$$

$$\Sigma_2 = x_1 - \frac{x_2 x_3}{\sigma} + \frac{1}{3\sigma^2} x_3^3$$

It can easily shown that the optimal control σ is u_{min} for $\Sigma_1 > 0$ while it is u_{max} for $\Sigma_2 < 0$.

The algorithm to find the quasi-optimal control over the interval $(0, \Delta t)$ for a pair of generators k and r involve the following steps:

1. Determine the relative velocity x_2 and acceleration x_3 of the k-th gen-

erator with respect to the reference machine.

2. Determine $\Sigma = x_2 - \frac{x_3^2}{2[L+b\,sgn(x_3)]} = 0$; $b<0$

3. Set $\alpha = u_{0min}$ if $\Sigma > 0$, otherwise $\alpha = u_{0max}$

4. If $\Sigma = 0$, $x_3 > 0$, $\alpha = u_{0min}$ otherwise $\alpha = u_{0max}$.

5. Determine

$$\Sigma_1 = x_1 - \frac{\pi}{2\omega_b} - \frac{x_2 x_3}{\sigma} + \frac{1}{3\sigma^2} x_3^3$$

$$\Sigma_2 = x_1 - \frac{x_2 x_3}{\sigma} + \frac{1}{3\sigma^2} x_3^3$$

6. If $\Sigma_1 \leqslant 0$ and $\Sigma_2 \geqslant 0$

$u(t) = u_{0min}$ if $\Sigma > 0$

$u(t) = u_{0max}$ if $\Sigma < 0$

7. If $\Sigma_1 > 0$, $u(t) = u_{0min}$

$\Sigma_2 < 0$, $u(t) = u_{0max}$

8. Once $u(t)$ has been determined for a particular time step, $u_x(t)$ and $u_r(t)$ are obtained by working backwards through equations (4.47), (4.48) and

(4.49). $L(t)$ and $b(t)$ are assumed to remain constant over the time step $[0, \Delta t]$.

9. Performing the first seven steps for $k=1,2,3.......n$, $k \neq r$ and determine quasi-optimal control for each generator for the time interval $(0, \Delta t)$. The control for the rth generation may be obtained from the first pair.

10. Once the control vector u for all the generators has been determined for the time interval $[0, \Delta t]$, the state equation (4.30) is solved for an integration step Δt. Here all the initial values of X and Y are available from the initial load flow of the system. At the end of the integration step, X is changed and Y is updated by a load flow calculation of equation (4.31).

The procedure is then continued for the time step $[\Delta t, 2\Delta t]$. The algorithm is discontinued if some convergence or divergence criteria are met.

To obtain smooth voltage regulation and to avoid excessive switching, a modification of the above control proportional to the switching function is used i.e.

$$u^*(t) = k\Sigma$$

This provides a smooth transition to normal voltage regulation at the expense of a longer settling time.

CHAPTER 5

SYSTEM SIMULATION

5.1 INTRODUCTION

This chapter describes the application of the proposed control strategy to stabilize three realistic test systems subjected to several transient disturbances:

i) 4 machine El-Abiad system given in reference[31],

ii) 7 machine system given in reference [44], and

iii) Bangladesh Power System.

In simulating the various conventional stability, the simplifying assumptions listed earlier were implictely adopted. For transient stability study a interactive power system simulation package was used. The methodologies applied here for both first swing and subsequent swing stability have been developed in chapter 4.

This chapter presents a brief description of the systems. The simulation results are presented in this chapter. Three situations are considered for each fault: without any control, only braking resistor and shunt reactor control and both resistor and excitation control acting together.

5.2 TEST SYSTEM 1

The 4 machine system [31] is widely used in different simulation techniques. The system is also used in this thesis to test the applicability of the developed methodologies.

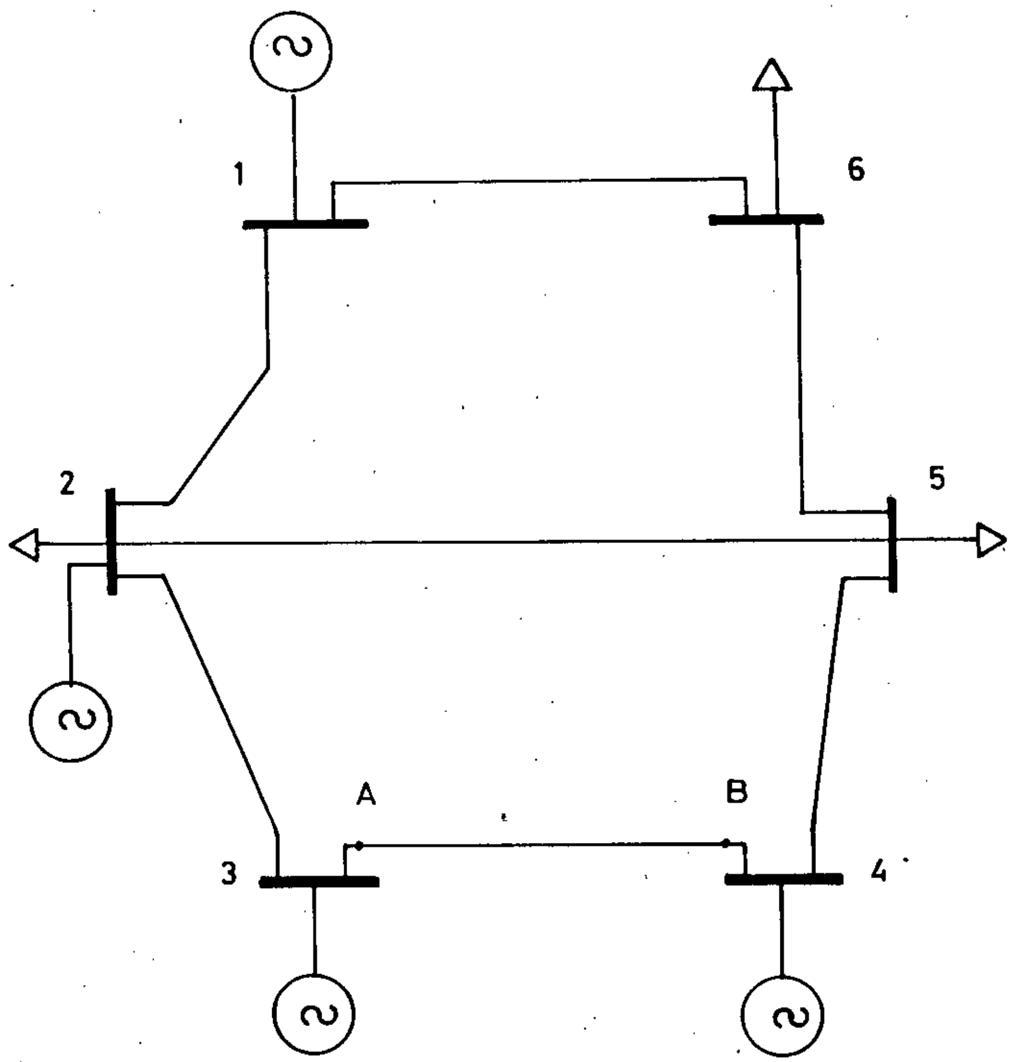


FIG. 5.1 TEST SYSTEM 1

5.2.1 4 Machine El-Abiad System [31]

The topology of 4 machine system given in figure 5.1 has been studied using both dynamic braking resistor and shunt reactor control and the quasi-optimal excitation control. The machine and network data and the load flow results are given in Appendix B.

Three phase faults were simulated at A and B in figure 5.1 separately. The faults were cleared by opening a line between respective buses. It is assumed that generators on both buses 3 and 4 are equipped with braking resistor and shunt reactor. The value of conductance (G_i) and susceptance (B_i) were considered to be 1 and 10 per unit respectively, as assumed in reference [31].

5.2.2 Result : Fault at Machine 3

Figure 5.2 shows the variation of all machine angles when a 3-Φ fault of 0.40 sec duration was applied at A. Angles of all the machines are with respect to machine 1. In this study, the process was abandoned if (i) δ exceeded 160° and (ii) real time was greater than 3 seconds.

As can be seen, machine 3 exhibits first swing instability. Figure 5.3 shows the variation of all machine angles with proposed closed loop stabilizing control consists of braking resistor and shunt control only under the same fault condition. The figure indicates that the unstable machines are stabilized with the braking resistor control. Although the system is stable the later swings are still considerably large. The oscillation with both controls acting simultaneously are significantly reduced. It is shown in the figure 5.4. A comparison of responses from the severely disturbed machine (#3) is given in figure 5.5. Figure 5.6 gives the variation of machine velocity (ω) with time for faulted machine. It is evident from this figure that with the excitation control, the speed deviation reaches nearly zero as desired. The variation of field voltage after the excitation control is applied is given in figure 5.7.

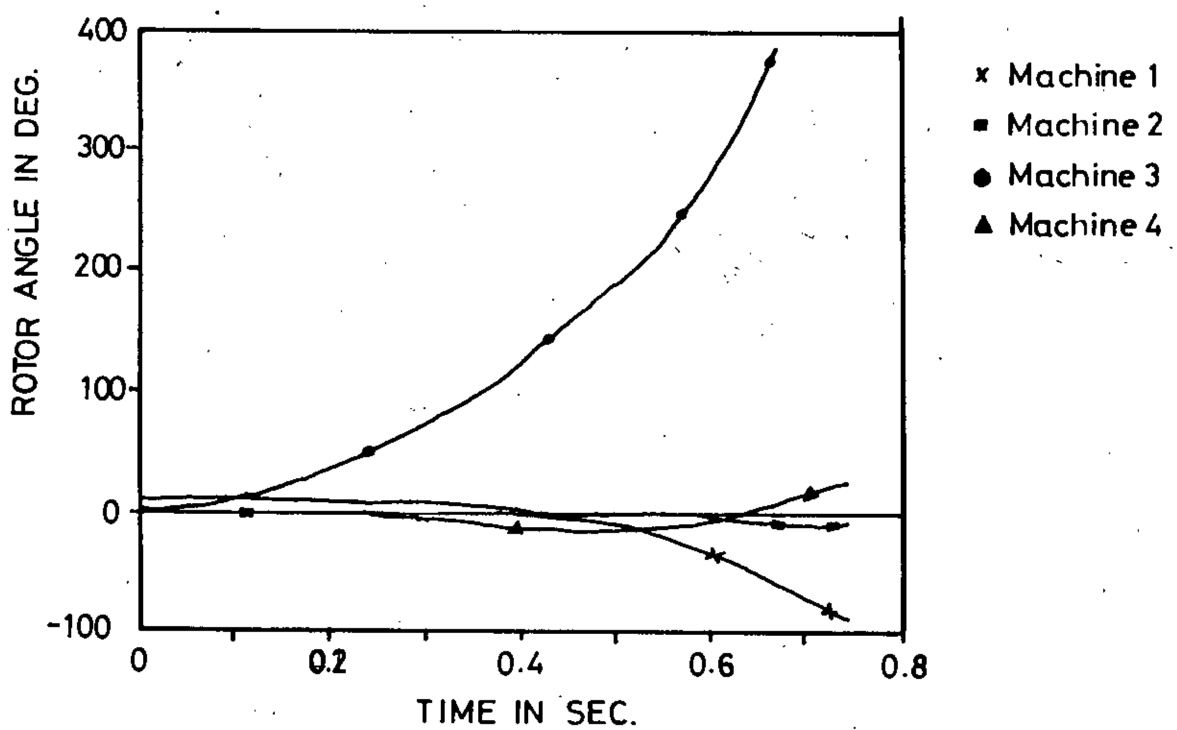


Fig. 5.2 Machine angle for 3-φ fault of 0.4 Sec. duration on Bus # 3 (without any control)

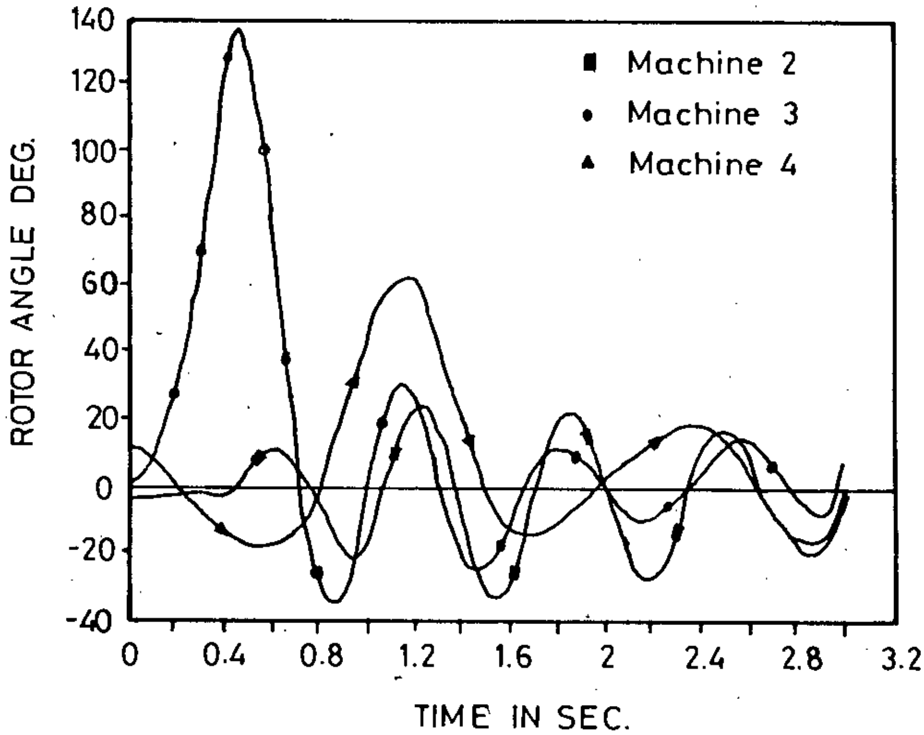


Fig. 5.3 Machine angle for 3φ fault of 0.4 Sec. duration on Bus # 3 with the proposed dynamic braking resistor and shunt control.

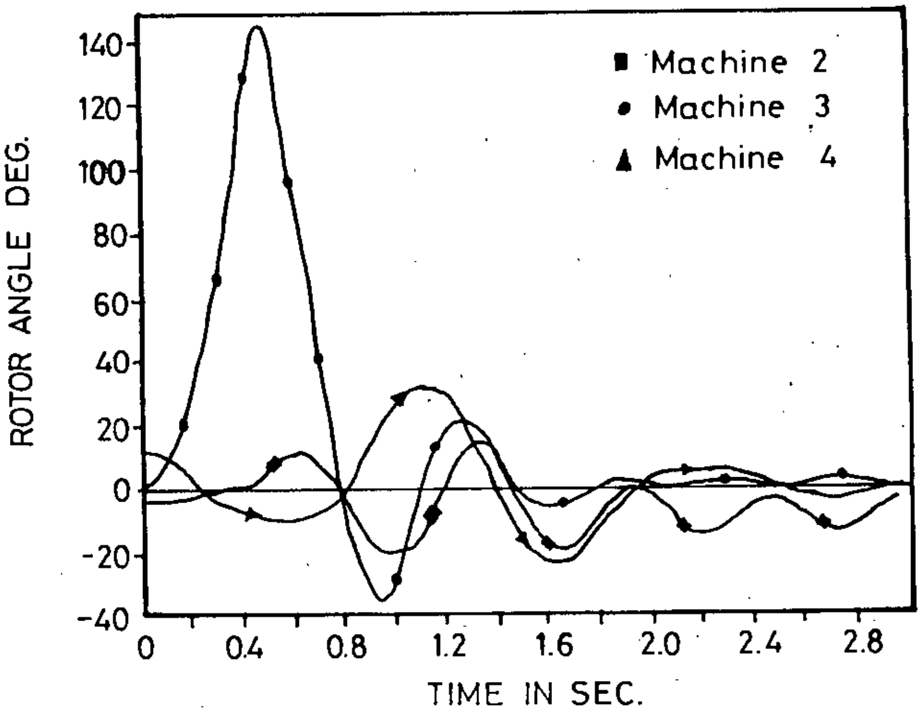


FIG. 5.4 Machine angle for 3-φ fault of 0.4 Sec. duration on Bus # 3 with both resistor and excitation control.

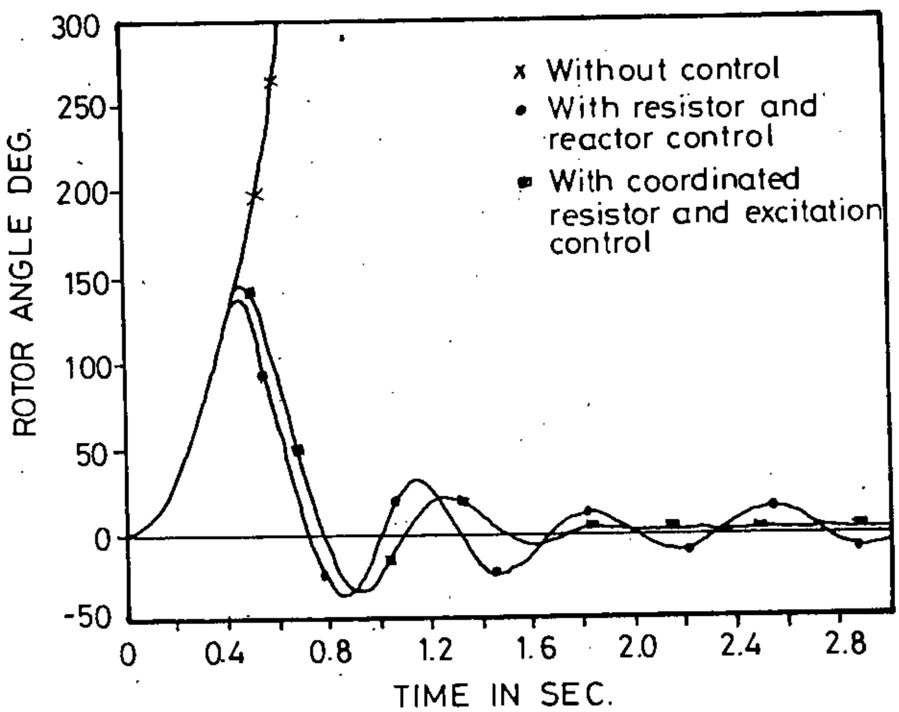


FIG. 5.5 Rotor angle variation with time for Machine # 3 without any control and with two quaist-optimal control schemes.

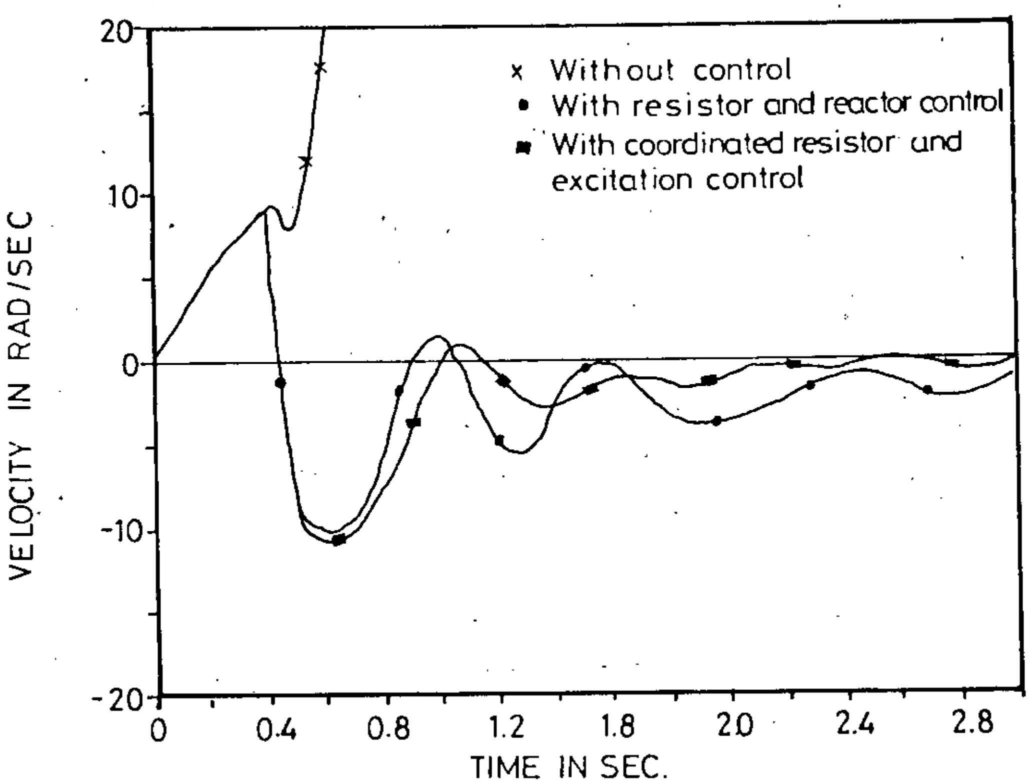


FIG.5.6 Velocity variation with time for machine # 3 without any control and with two proposed scheme.

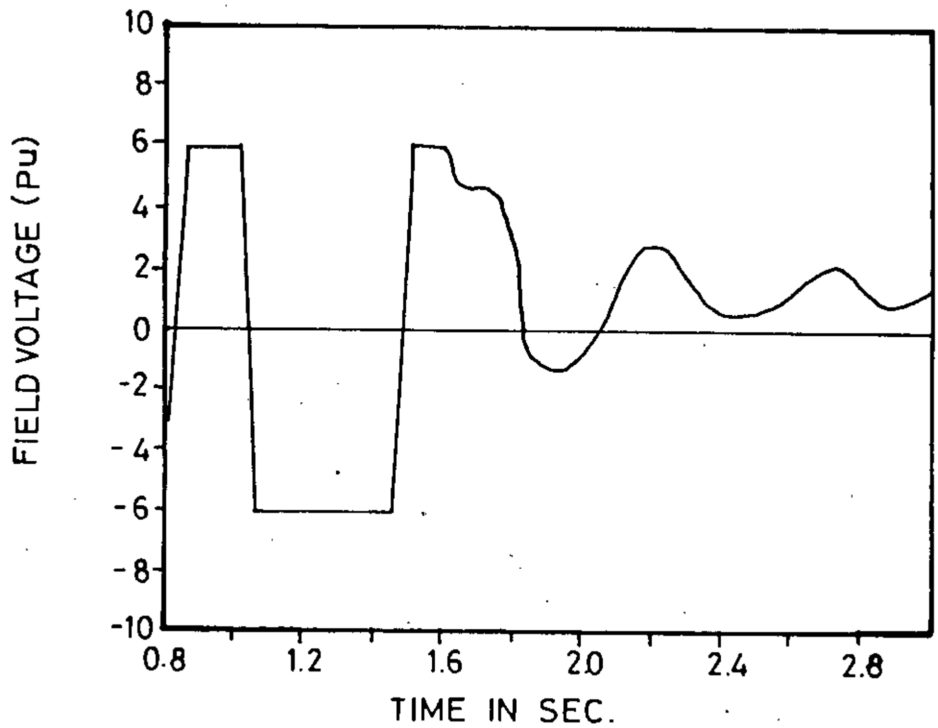


FIG. 5.7 Field voltage variation after the exciter is called with time

5.2.3 Results: Fault at Machine 4

Similarly a 3-φ fault of 0.5 sec duration was applied at B(Fig.5.1). Figure 5.8 shows the variation of machine angles under the fault situation. Machine # 4 is unstable in this case. Figure 5.9 shows the machine angles variation with time applying dynamic braking resistor and shunt reactor only. The figure shows that though the unstable machine is stabilized with the braking resistor control, the later swings are still considerably large. The response with both the control acting simultaneously is much better. It is shown in the fig. 5.10. A comparison response from machine #4 is given in Fig. 5.11. Field voltage variation is shown in fig. 5.12. In this study, the process was abandoned if (1) δ exceeded 160° or (ii) real time was greater then 6 secs.

5.2.4 Closing Comment

Table 5.1 gives the summary of the switching history for the test system 1.

Fault on bus	Critical clearing sec.	machine no.	Fault on sec.	Brake on sec.	Reactor on sec.	Exciter called sec
3	0.39	3	0.0-0.40	0.35-0.50	0.52-0.80	0.82
4	0.49	4	0.0-0.5	0.45-0.63	0.68-1.25	1.26

Table 5.1 Summary of the switching history of 4-machine system

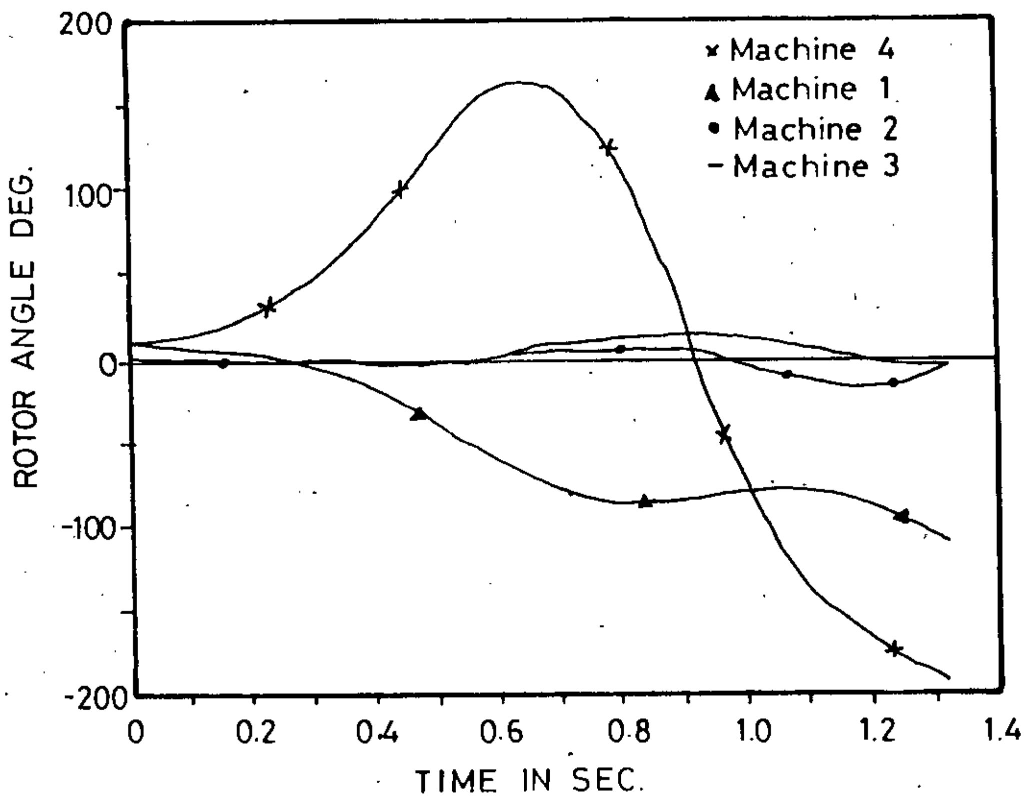


FIG. 5.8 Machine angles variation for 3-φ fault of duration 0.5 Sec. on bus # 4 (without any control)

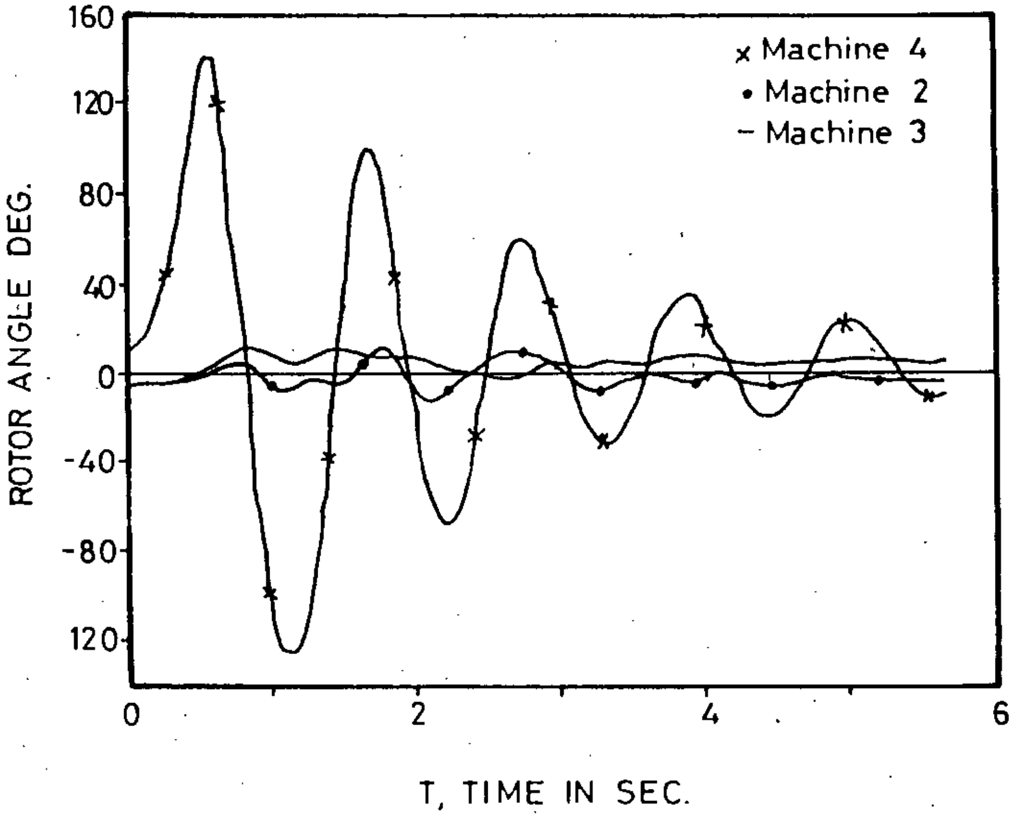


FIG. 5.9 Machine angle for 3-φ fault on bus # 4 with the braking resistor and reactor control

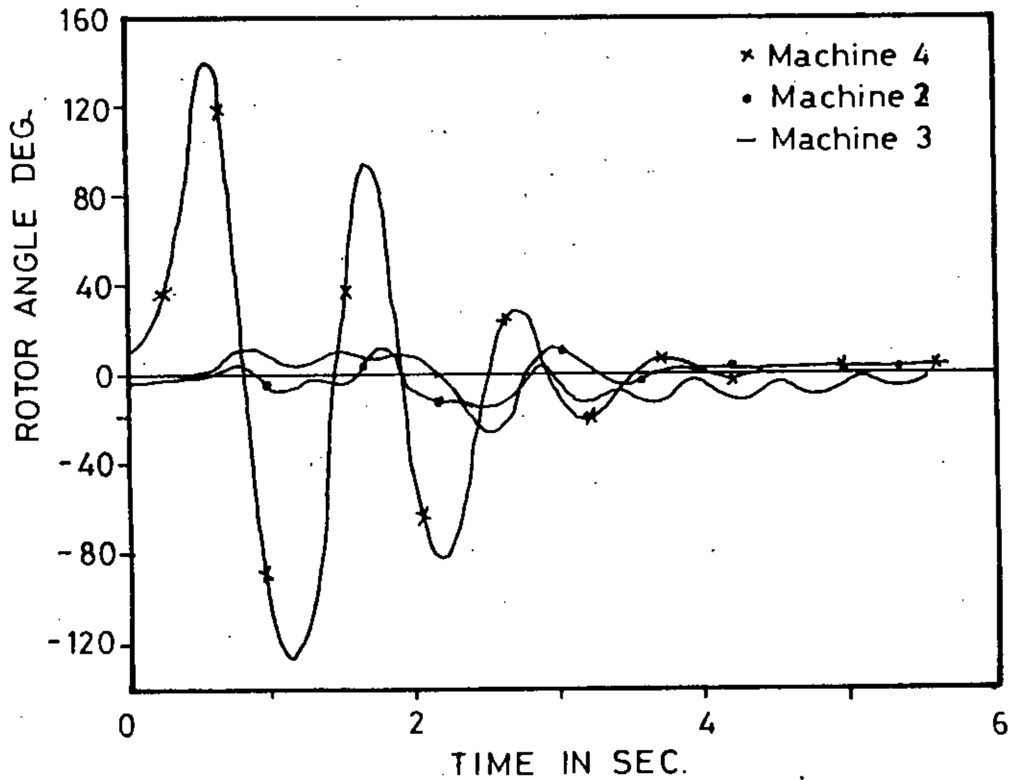


FIG. 5.10 Machine angle for 3-φ fault on bus # 4 with two quasi-optimal control scheme

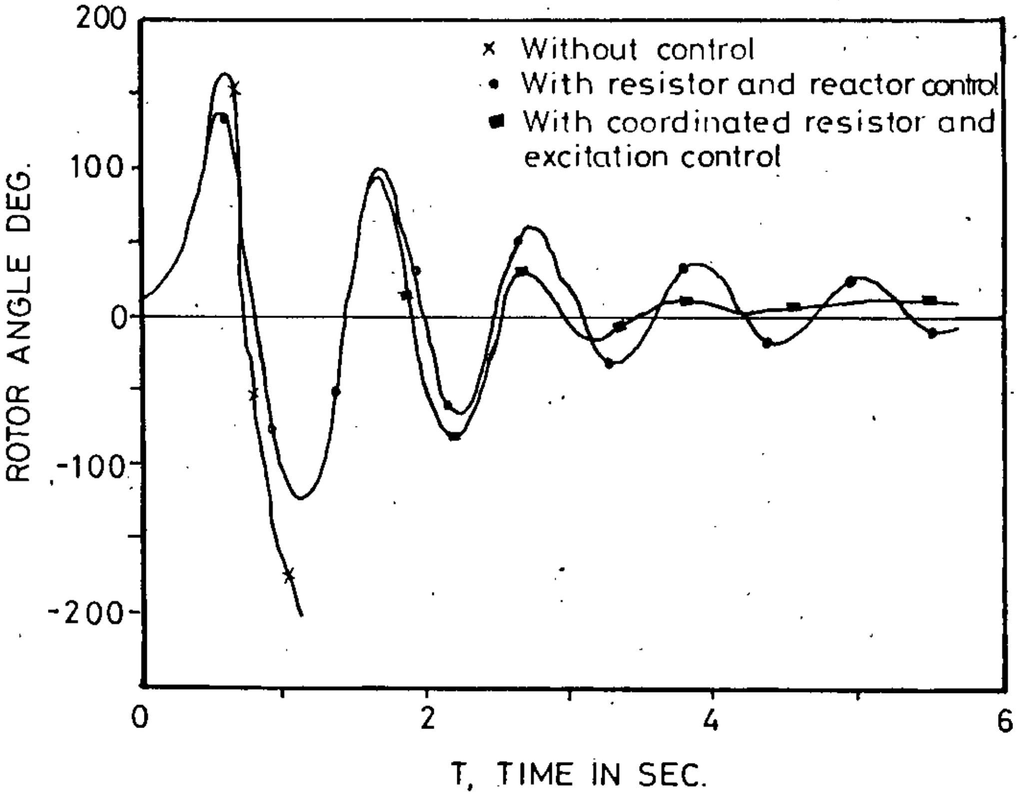


FIG. 5.11 Rotor angle varition with time for machine #4without and with two quasi-optimal control schemes

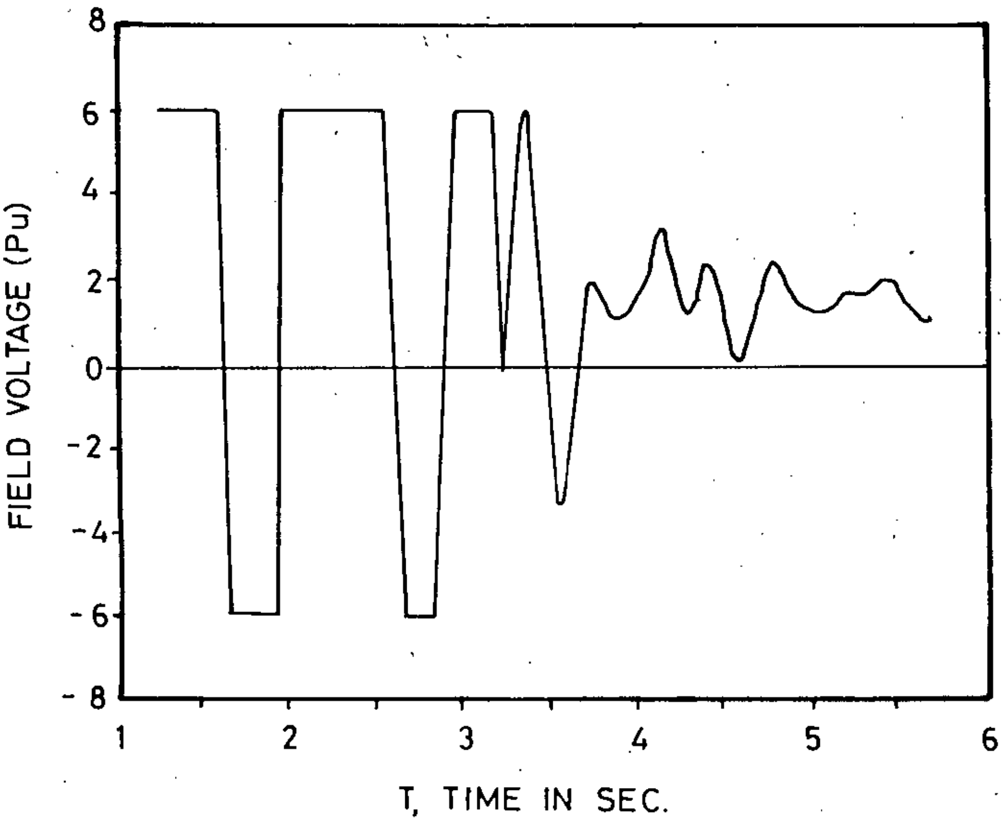


FIG. 5.12 Variation of field voltage with time

5.3 TEST SYSTEM 2

Here we consider 7 machine system to test the proposed two quasi-optimal control scheme.

5.3.1 7 Machine CIGRE System

The 7 machine system given in reference [44] is tested first with the dynamic resistor and shunt reactor control strategy and then with the coordinated braking control and excitation control scheme. Fig. 5.13 gives the system network; the machine and network data and the load flow results are given in Appendix B.

Three phase faults are simulated at A and B in figure 5.13 separately. It is assumed that generators 1 and 6 both are equipped with braking resistor and shunt reactor. Here also the process was abandoned if (i) δ exceeded 160° or (ii) time was greater than 6 secs.

5.3.2 Results: Fault at Bus 1

Figure 5.14 shows the variation of all machine angles when a 3 - φ fault of duration 0.4 sec was applied at A. Angles of all the machines are with respect to machine 4.

As can be seen machine 1 shows first swing instability. Figure 5.15 indicates the variation of all machine angles with dynamic brake and shunt reactor control only. 5.16 shows the variations with braking resistor and excitation control acting together where later swings are stabilized markedly. Angle of variation with time of disturbed machine #1 is shown in figure 5.17. Figures 5.18 and 5.19 show the velocity variations of machine #1 and field voltage variation respectively.

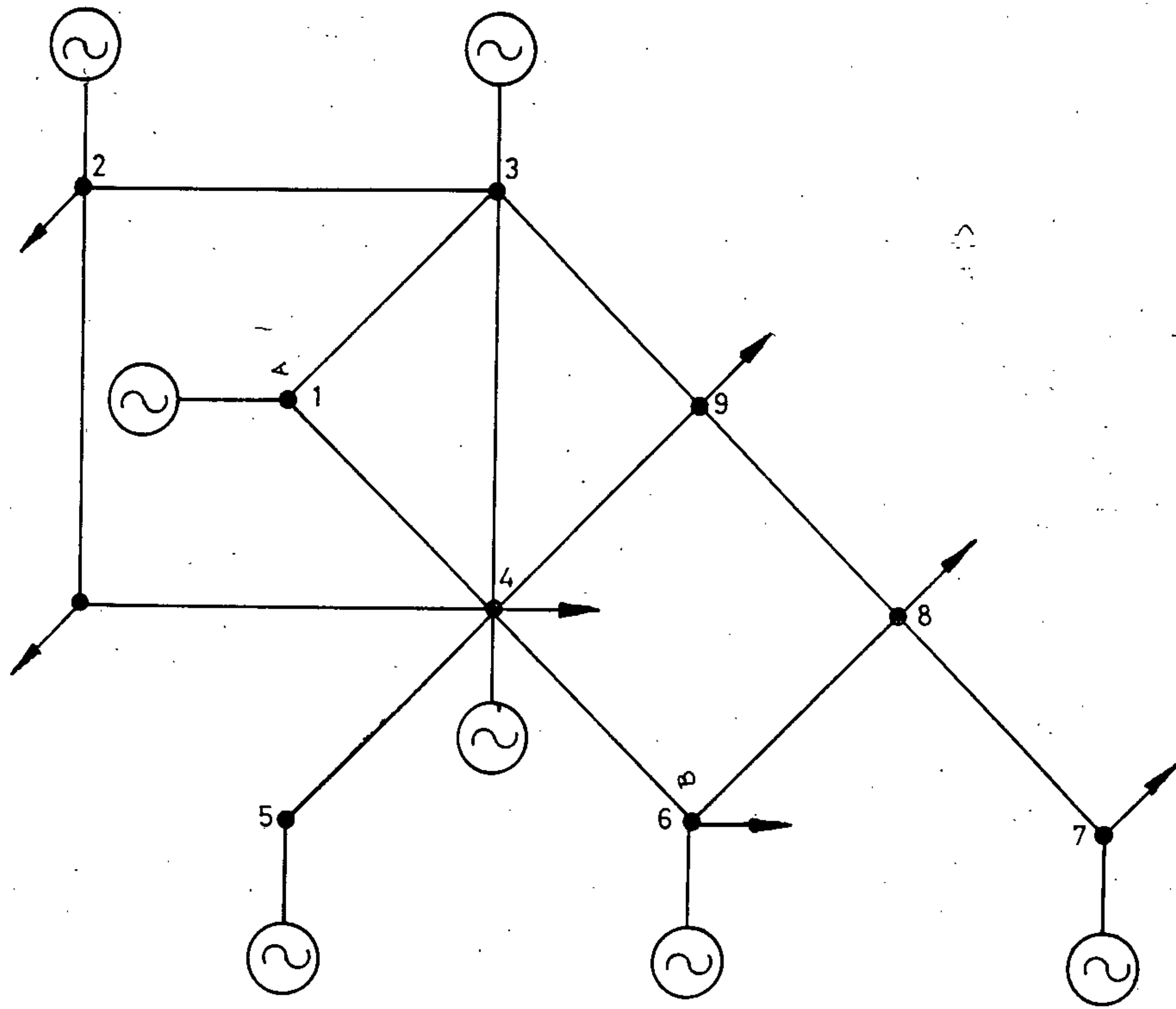


FIG. 5.13 TEST SYSTEM 2

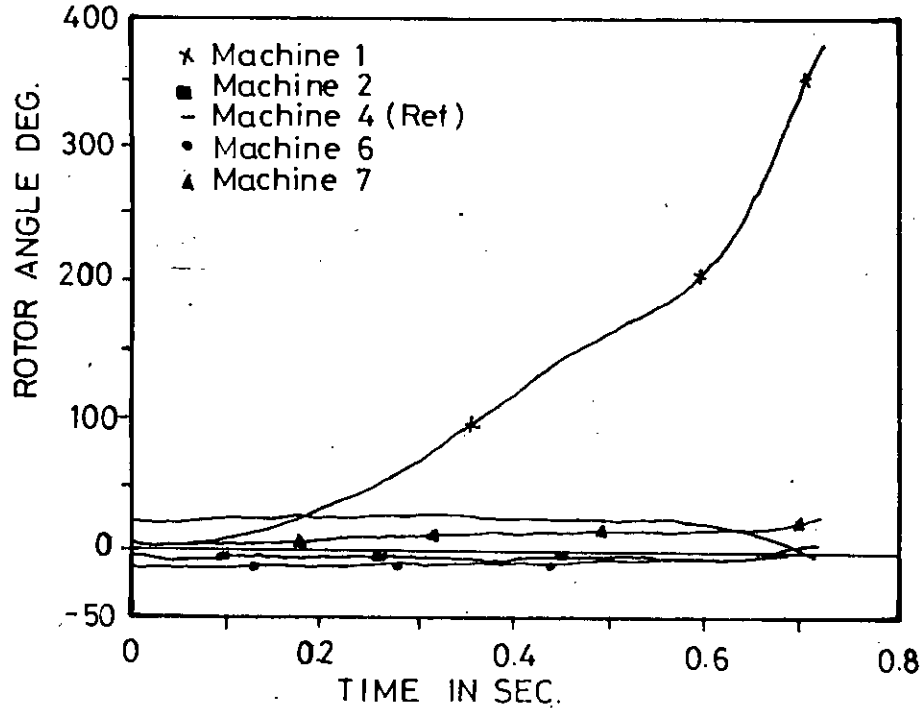


FIG. 5.14 Machine angles for 3-φ fault of duration 0.4 Sec on machine terminal # 1 (without control)

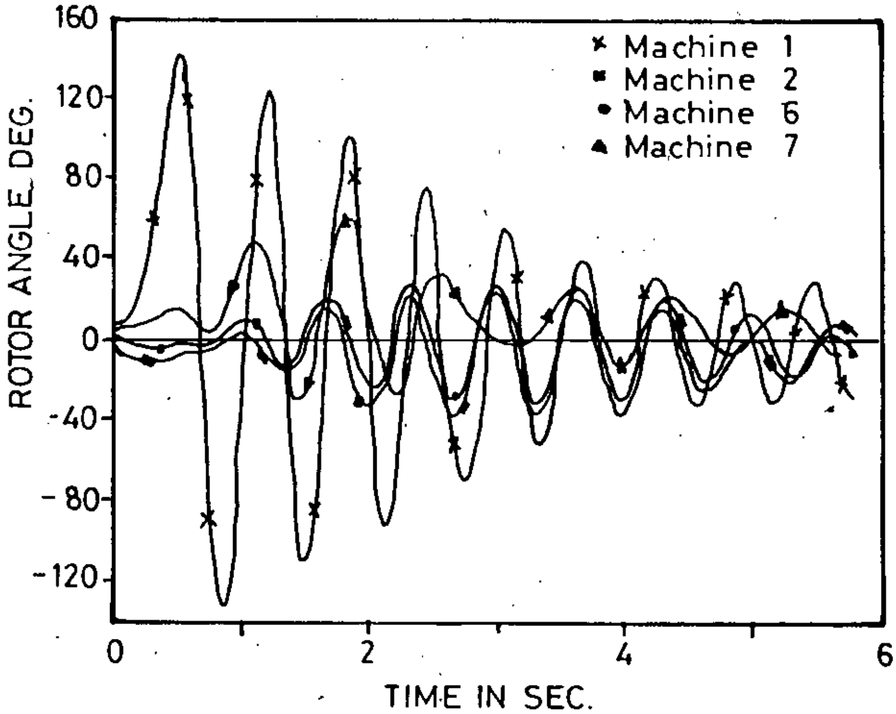


FIG. 5.15 Machine angles for fault at 1 with dynamic braking resistor and shunt control only

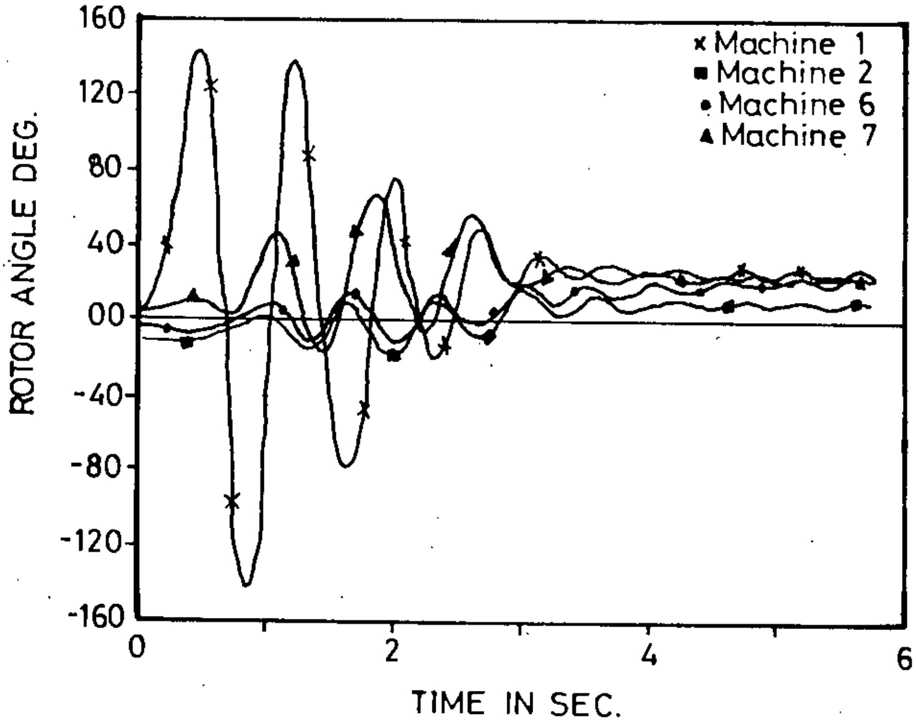


FIG. 5.16 Angle variation with time with proposed two quasi-optimal control scheme

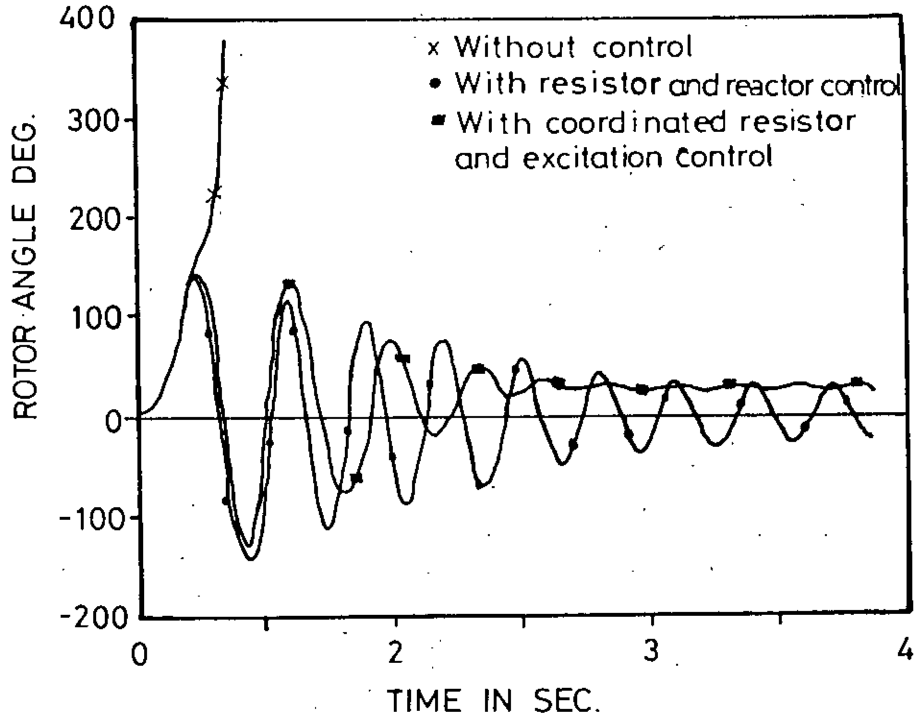


FIG. 5.17 Rotor angle of machine 1 without and with the proposed schemes

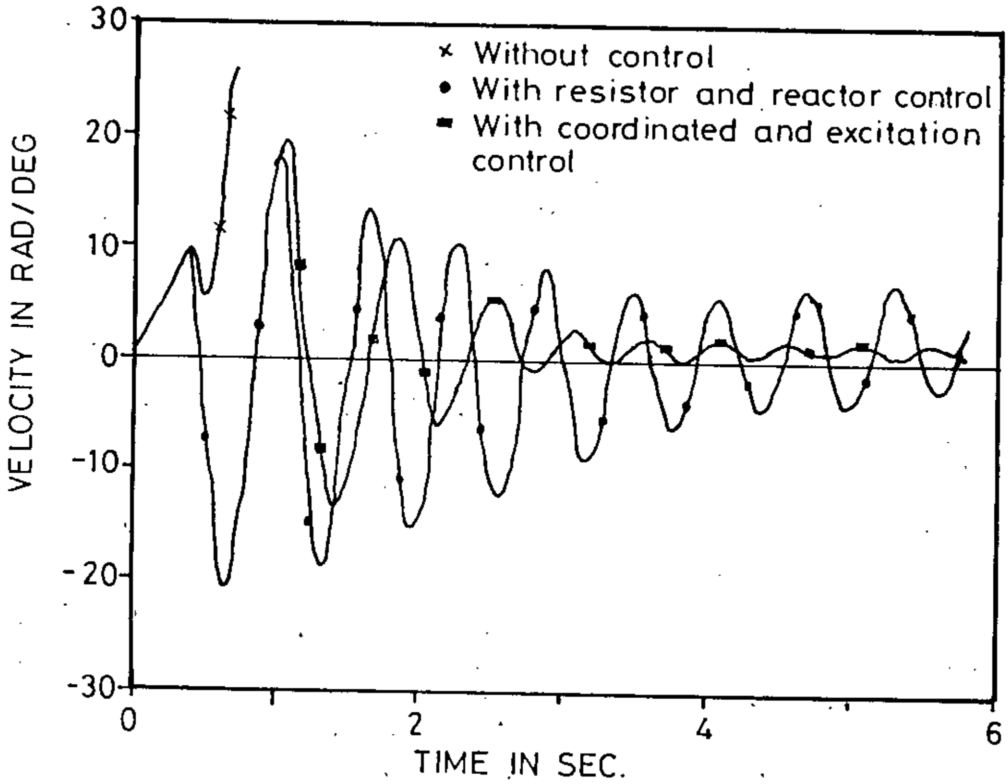


FIG. 5.18 Velocity variation of machine # 1 without and with control schemes

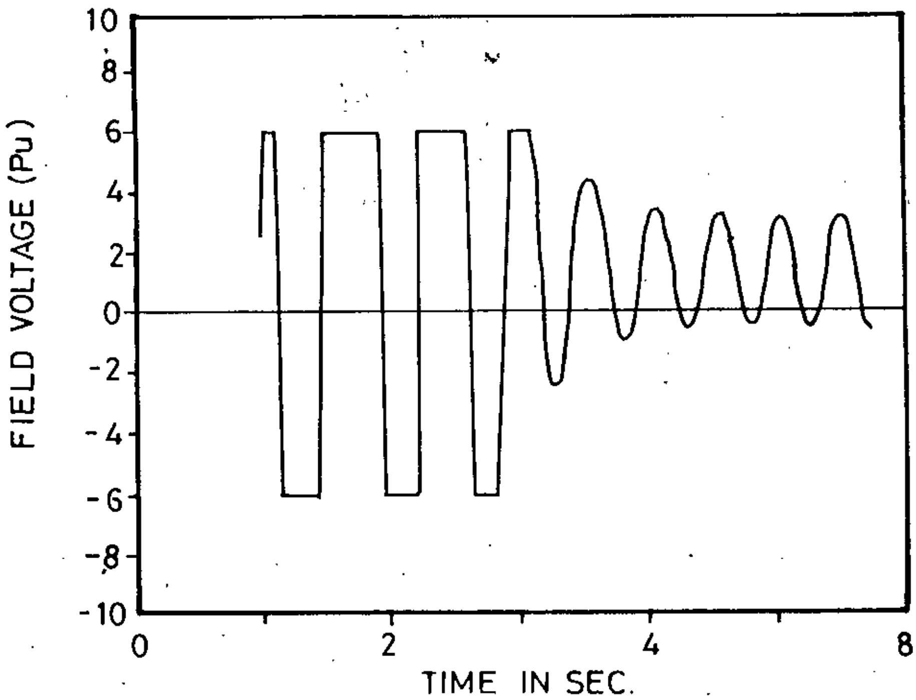


FIG. 5.19 Field voltage variation after exciter is called with time

5.3.3 Results: Fault at Machine 6

A 3 -φ fault of duration 0.52 sec was applied at B (figure 5.13). Fig. 5.20, 5.21 and 5.22 shows the variation of machine angles without control, with only brake and reactor control and with coordinated proposed brake and excitation control scheme. A comparison of response from the severely disturbed machine (#6) is given in figure 5.23. Velocity variation and field voltage variation of machine #6 are given in figure 5.24 and 5.25.

5.3.4 Closing Comment

Table 5.2 gives the summary of the switching history for the test system 2 of 7 machines.

Fault on machine no.	Critical clearing sec	Machine no.	Fault on sec	Brake on sec	Reactor on sec	Exciter on sec
1	0.39	1	0.0-0.40	0.35-0.65	0.69-0.95	0.97
6	0.51	6	0.0-0.52	0.42-0.60	0.72-1.00	1.00

Table 5.2 Summary of the switching history of 7 machine system

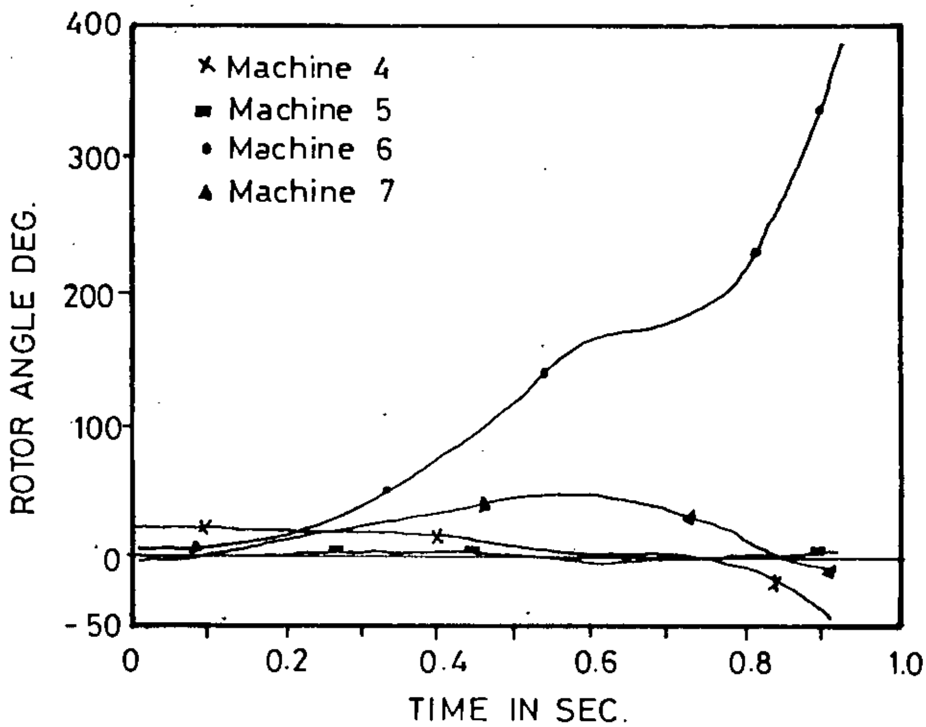


FIG. 5.20 Machine angles for 3-φ fault of duration 0.52 Sec. on machine # 6 (without control)

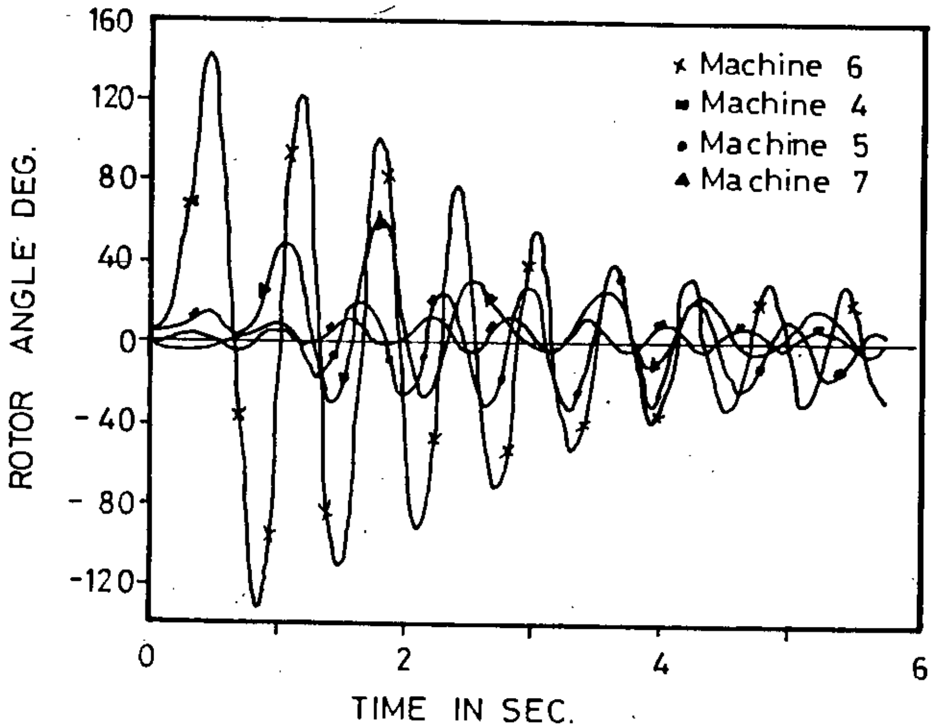


FIG. 5.21 Machine angles with dynamic brake and reactor only

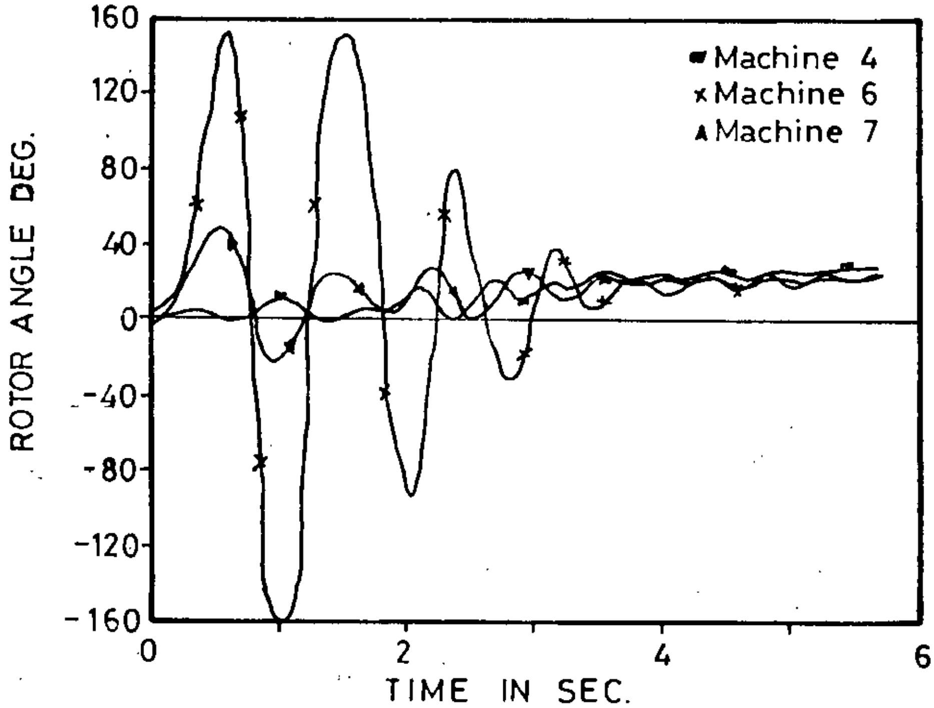


FIG. 5.22 Machine angles with two quasi-optimal proposed control scheme

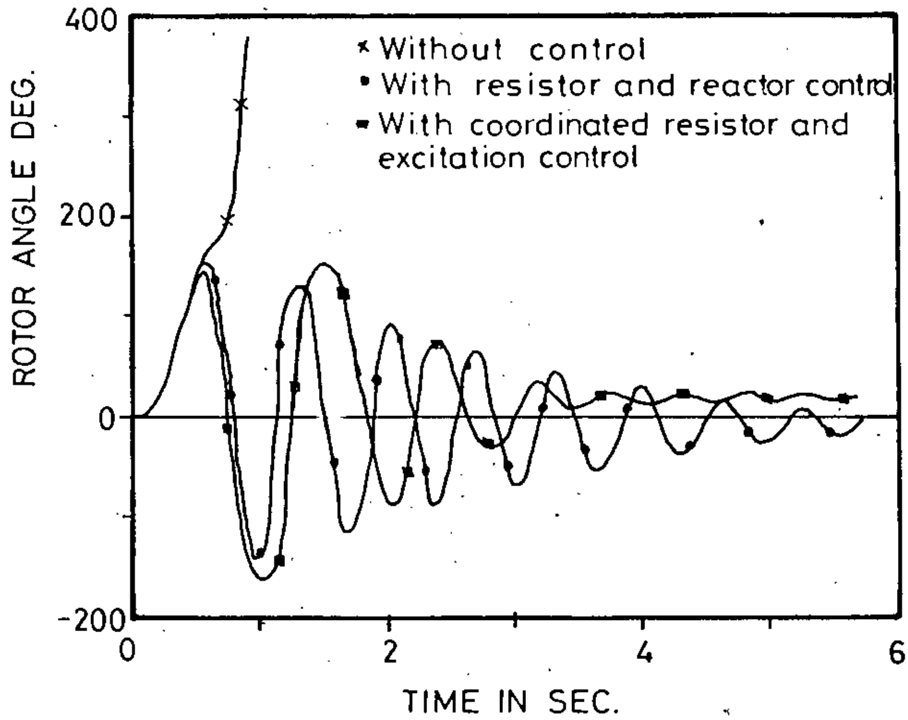


FIG. 5.23 Rotor angle variation with time for machine # 6 without and with control schemes

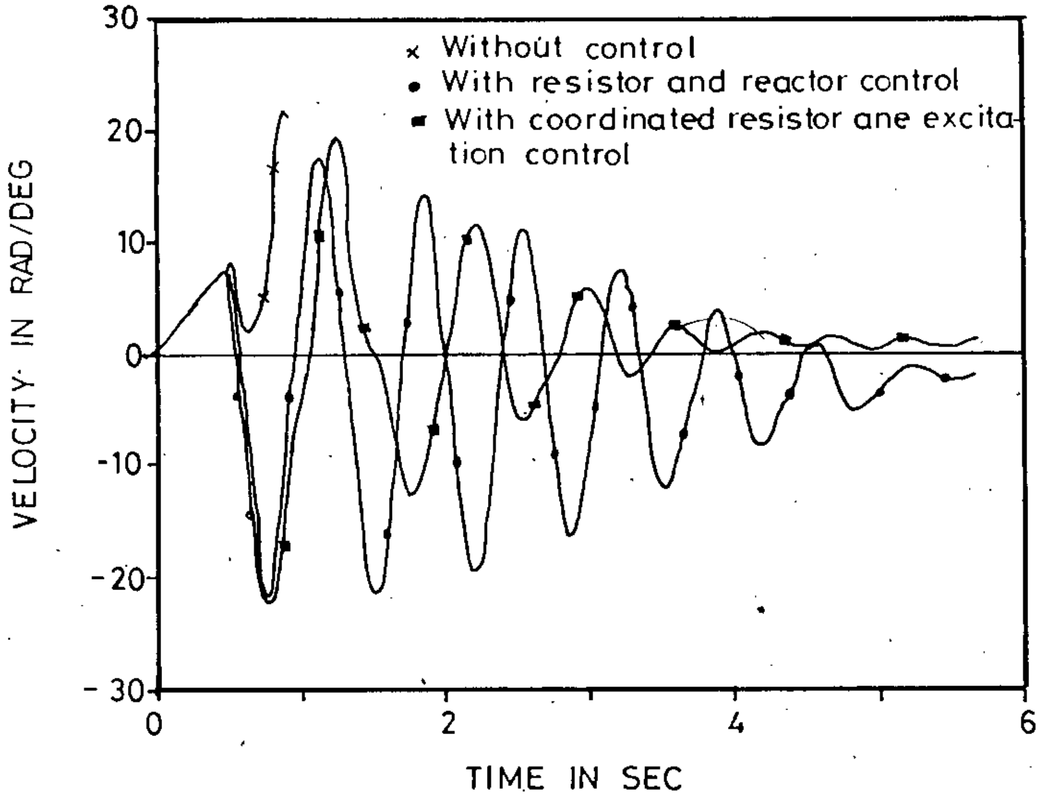


FIG. 5.24 Velocity variation of machine #6without and with control schems

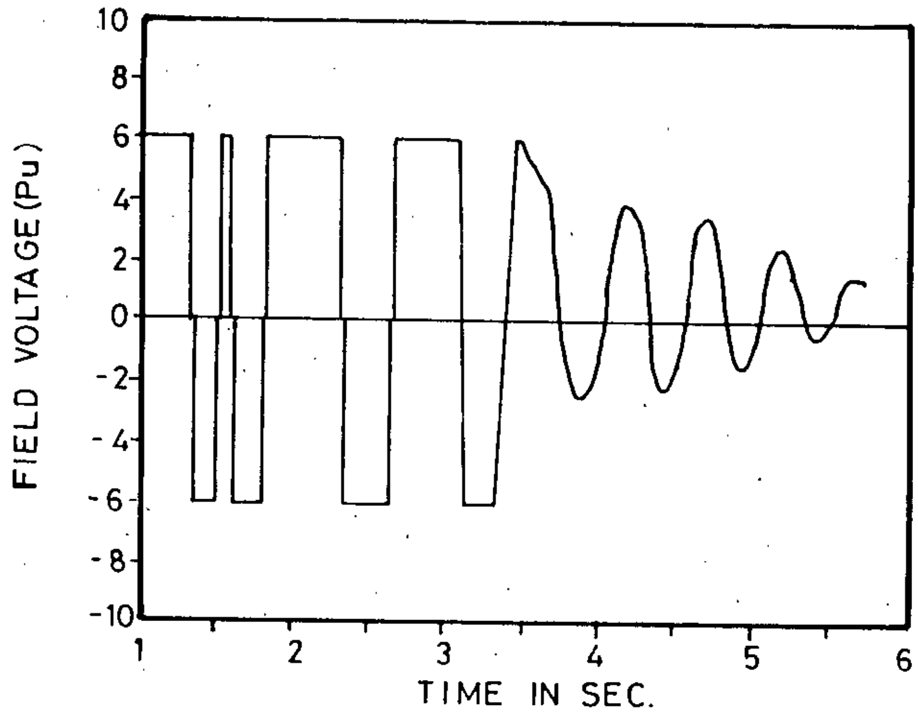


FIG. 5.25 Field voltage variation after exciter is called of machine

5.4 TEST SYSTEM 3

The control strategy was also tested on a relatively larger sytem - Bangladesh power network.

5.4.1 Bangladesh Power Network

The network diagram given in figure 5.26 is the topology of 11 machine 34 bus reduced Bangladesh Power Network. This power system may be divided into two zones: the East zone and the West zone separated by the rivers Padma, Jamuna and Meghna. The pecularity of this system is that a double circuit relatively long line between TONH and ISUH connects these two separate grids. This connector is East-West Interconnector forming an integrated national grid. Out of 11 generating plant there is only 1 Hydro plant and 10 thermal plants. Bangladesh Power Development Board (BPDB) has the sole responsibility of generating, transmitting and distributing the electric energy in Bangladesh. The generator and network data are given in Appendix B.

It is assumed that all the generators except the reference machine (Ghorasal Main Grid--GHMG) are equipped with control means. Thus the control is made entirely of local variables (except δ_r). Two cases were studied with different fault locations. The values of conductance and susceptance were considered to be 1 and 10 p.u. respectively. The process was abandoned if (i) δ exceeded 160° amd (ii) real time was greater then 6 secs.

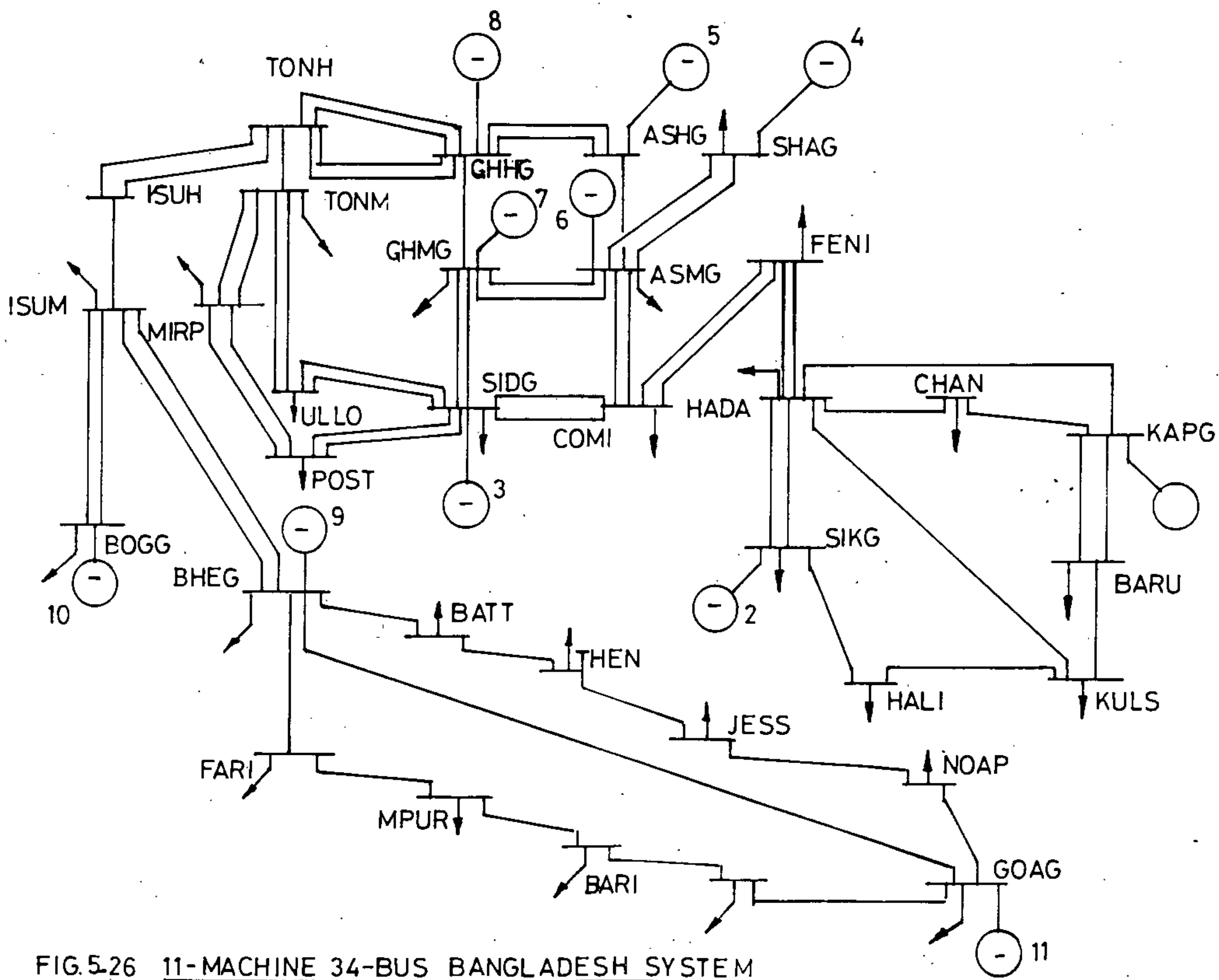


FIG. 5.26 11-MACHINE 34-BUS BANGLADESH SYSTEM

5.4.2 Results : Fault at Bus Kaptai Grid (KAPG)

A 3 $-\varphi$ fault was simulated at bus KAPG cleared after 0.42 secs. The critical clearing time is 0.4 sec. Figure 5.27 shows the variation of machine angles without any control (severely disturbed machine responses are plotted). As can be seen, the generators at bus KAPG and SIKG exhibit first swing instability. The state response with brakes are shown in figure 5.28. Fig. 5.29 shows the response of machine KAPG without control, with brake and reactor control and with coordinated brake and excitation control. 5.30 shows that of machine SIKG for above three cases.

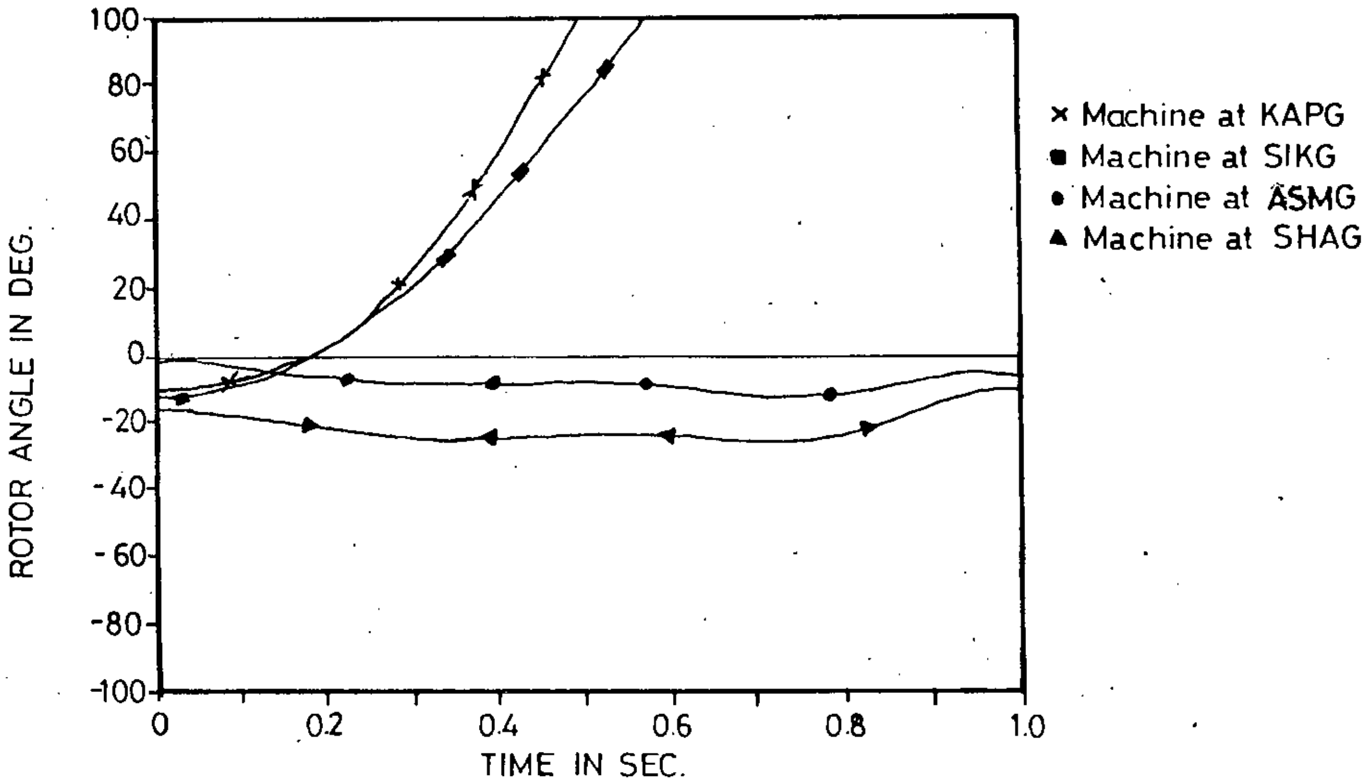


FIG. 5.27 Response without control for a 3φ fault on bus KAPG cleared after 0.42 Sec.

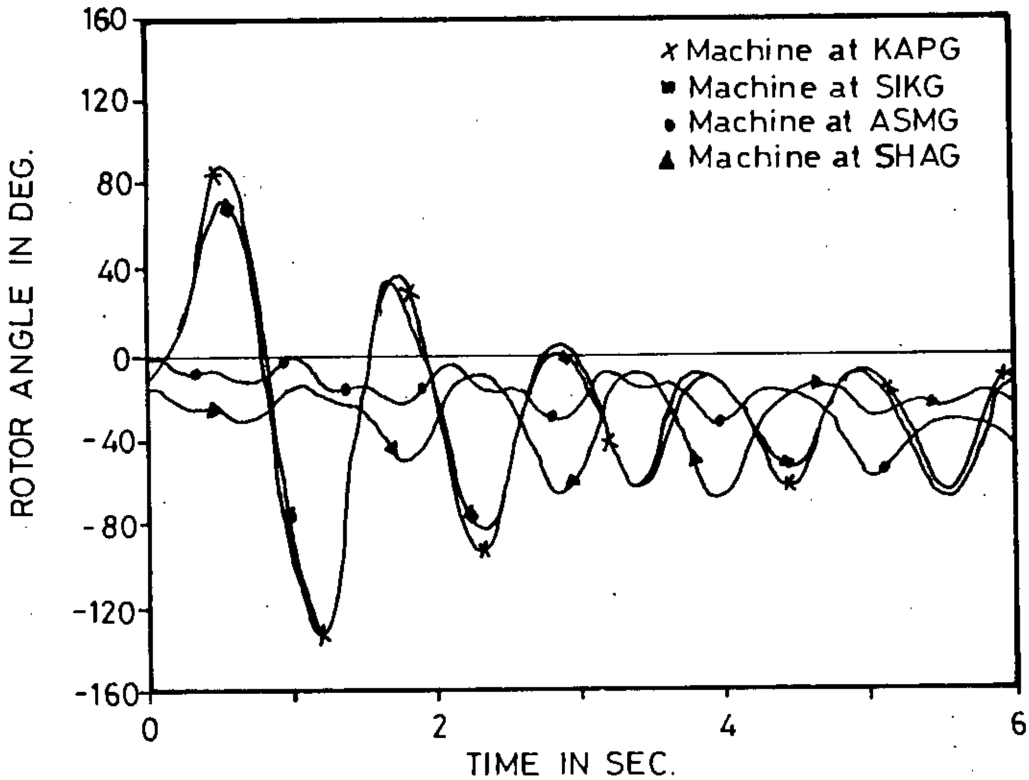


FIG. 5.28 Response with braking resistor and shunt control for a 3φ fault on bus KAPG

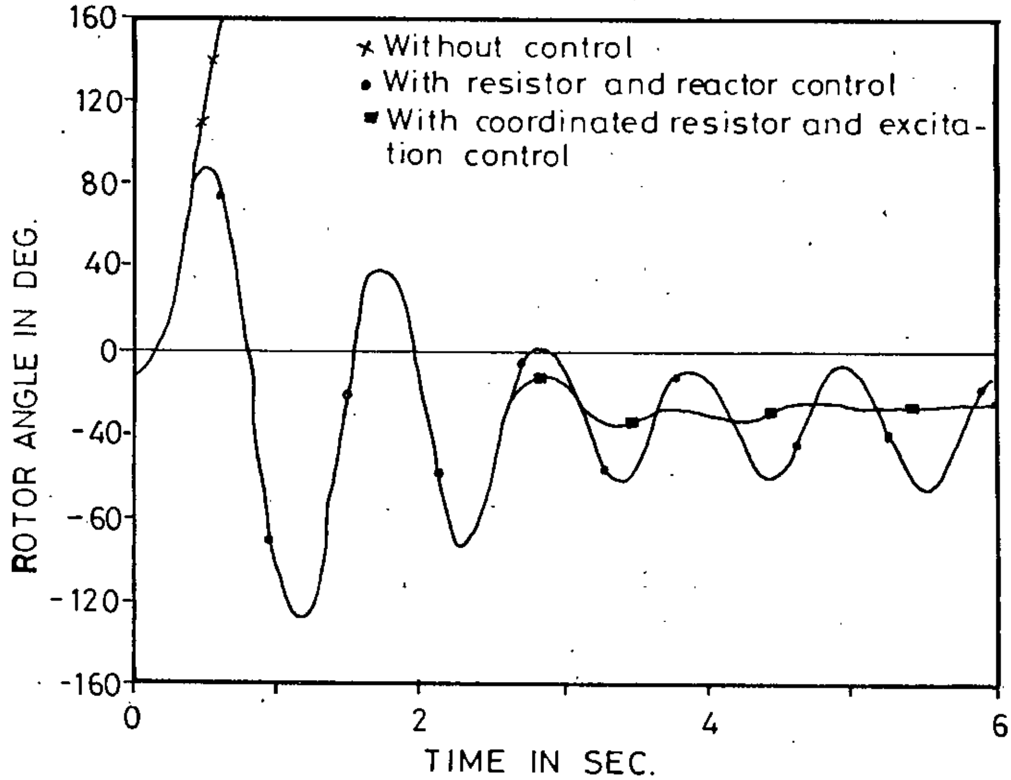


FIG. 5.29 Response of Machine KAPG without control, with braking resistor control and with braking resistor and excitation control.

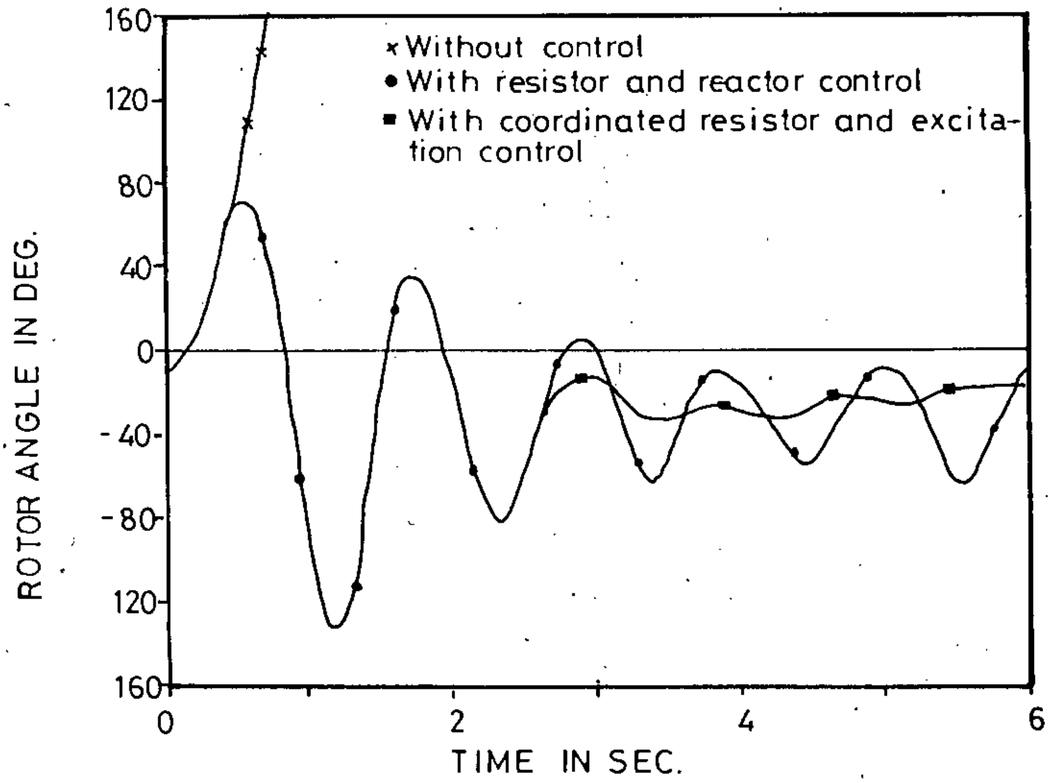


FIG. 5.30 Response of Machine SIKG without control, with braking action and with coordinated control scheme.

5.43 Results : Fault at Bus Sikalbaha Grid (SIKG)

A 3 -φ fault was simulated at bus SIKG for a fault duration of 0.44 secs. The critical clearing time was 0.43 secs for this fault condition. Figure 5.31 shows the unstable system response without any control. The machine at bus SIKG is unstable as can be seen from the figure. After application of the brake and shunt reactor according to the proposed control algorithm the system is stabilized as shown in figure 5.32. Figure 5.33 shows the response of faulted machine SIKG without control, with the braking resistor and shunt reactor control and with the proposed coordinated control algorithm.

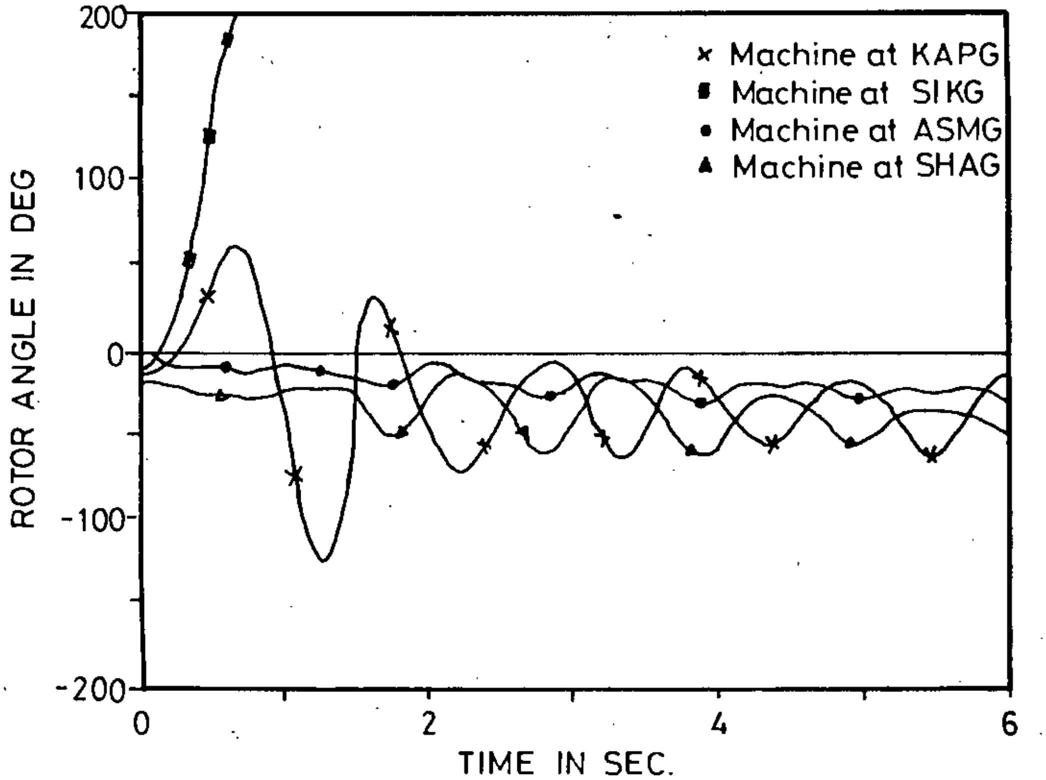


FIG. 5.31 Response without control for a 3φ fault on bus SIKG cleared after 0.44 Sec.

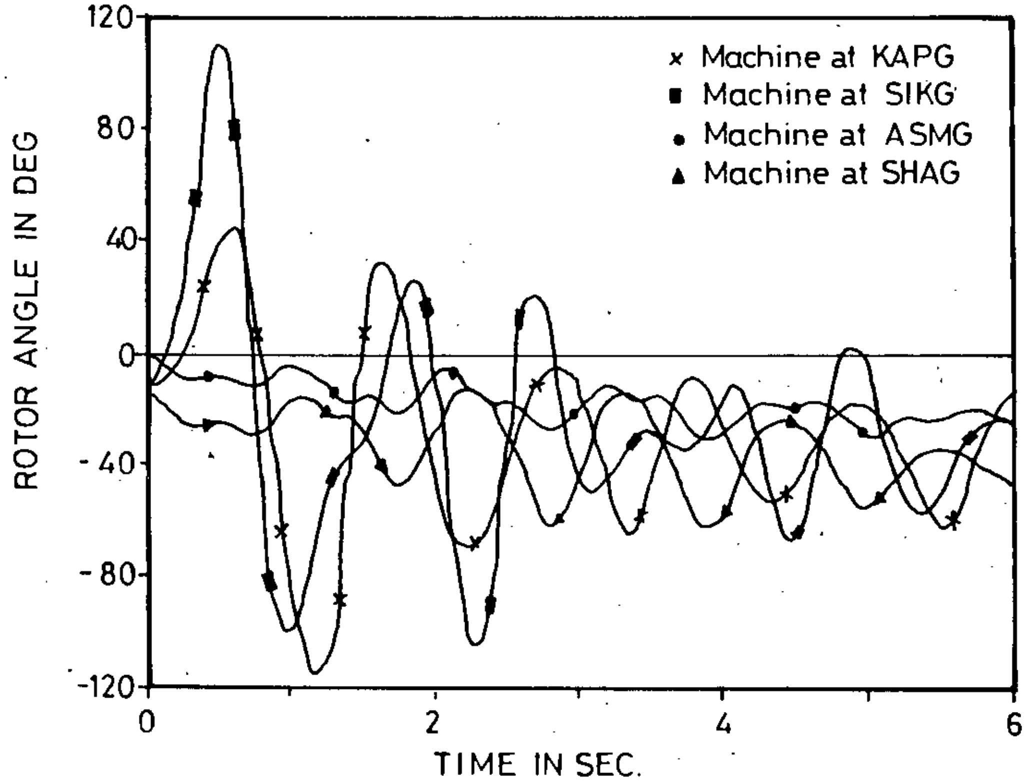


FIG. 5.32 Response with braking resistor and shunt control for a 3φ fault on SIKG

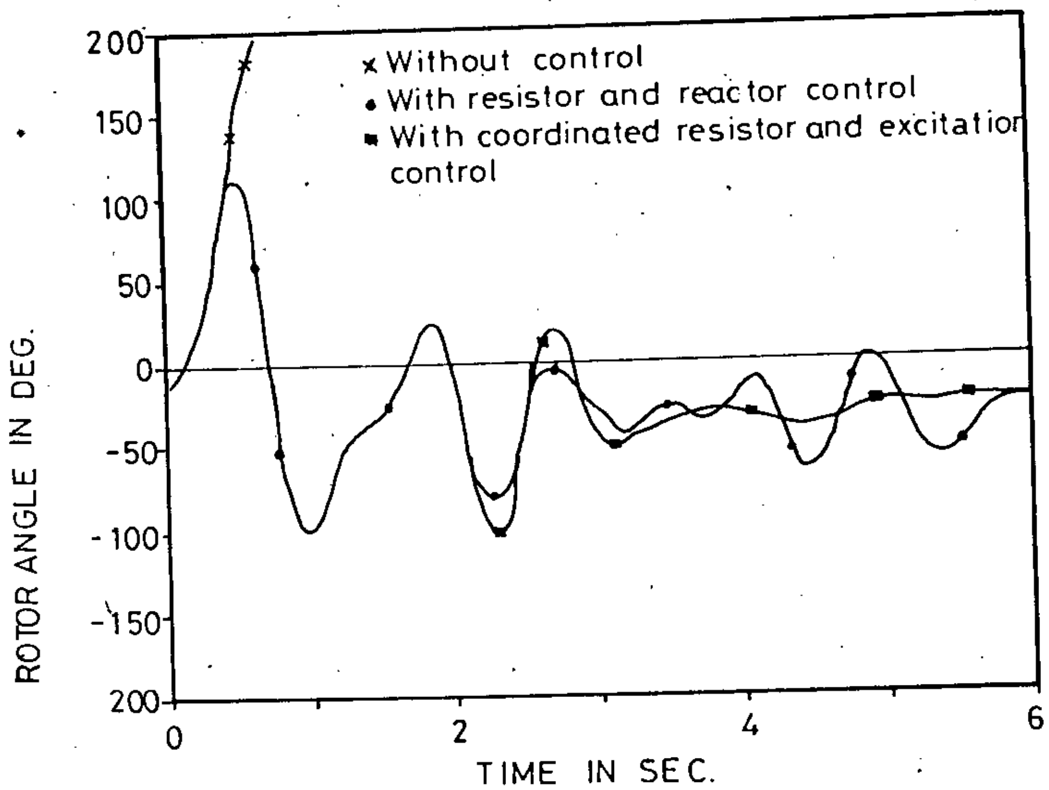


FIG. 5.33 Response of Machine SIKG without control, with braking resistor and shunt control and with coordinated control scheme.

5.4.4 Closing Comment

From the two study on Bangladesh power system, it is shown that when a fault is applied to bus SIKG, only machine at SIKG exhibits first swing instability, machine at KAPG is affected but machines at ASMG and SHAG are somewhat stable. The other machines are not so affected which are not shown. When a fault is applied to bus KAPG, machines at KAPG and SIKG shows first swing instability but all other machines are somehow stable. The proposed control scheme manage to stable the faulted unstable machines.

Table 5.3 gives the summary of the switching history for Bangladesh Power Network.

Fault on bus	Critical clearing time sec.	Machine at	Fault on sec.	Brake on sec.	Reactor on sec.	Exciter on sec.
KAPG	0.40	KAPG	0.0-0.42	0.4-0.8	0.81-1.28	1.3
		SIKG	0.0-0.42	0.4-1.0	1.1-1.5	1.51
SIKG	0.43	SIKG	0.0-0.44	0.42-0.64	0.65-1.28	1.29

Table 5.3 Summary of the switching history of BPS

CHAPTER 6

CONCLUSIONS

6.1 CONCLUSIONS

In this thesis, a quasi-optimal real-time coordinated feedback control strategy for dynamic resistor-shunt reactor and excitation control is proposed for total stabilization of power systems. The time optimal control of using dynamic brake and shunt reactor has been obtained as a function of synchronous machine power, its rotor angular position and speed deviation. Whereas the excitation control scheme has been also obtained directly of a function of relative rotor angle, frequency and acceleration of different synchronous machine of the system. These two quasi-optimal minimum time control strategies were applied sequentially to control transiently disturbed machine. The control problem was formulated into a minimum time control problem which gave a very effective "quasi-optimal" closed loop scheme to stabilize both transient and dynamic instability. This localised aim feedback control scheme require very little online computation using relatively little hardware (as it is not necessary to solve the system differential equation) and simple local measurements. The strategy is adaptive in that the control is a function of velocity and acceleration etc.which depend on the conditions existing at the time.

After a large disturbance, the faulted machine expresses a first swing instability. To control this instability, the quasi-optimal dynamic braking and shunt reactor control is very effective. Though the system is stable, the later swings are considerably large. In the latter case, modern fast excitation systems can be very effectively employed to wipe out smaller swings. In this thesis, these two quasi-optimal controls were used sequentially following the fault.

In order to formulate the mathematical model of the proposed control scheme, first the dynamic models were chosen and then Pontryagin's minimum principle was used to develop an "optimal" control based on a reasonably specified criterion. A "quasi-optimal" closed loop scheme was then presented.

The theory derived for the single machine system has been extended to a multi-machine system. It has been shown that if the reference machine in the multi-machine system is relatively large and is not equipped with braking resistor and shunt reactor control, then the control strategy for each machine is exactly similar to that of the single machine case. This means that in this case the control can be expressed in terms of variables local to each machine.

The control scheme has been tested on three multi-machine systems - a 4 generator system, a 7 generator system and 11 generator Bangladesh system. For each case, the system has been simulated without control, with the dynamic braking resistor and shunt reactor control and with the coordinated sequential application of dynamic brake, shunt reactor and excitation control. Results indicate that the braking control stabilize the unstable system and the excitation control wipe out the subsequent oscillations which are generally desired. For BPS the proposed algorithm is also effective in controlling first swing and subsequent swings stability.

The 4 machine system were studied by other researchers. They used a reduced single machine equivalent model for multimachine system to determine the switching of the resistor, reactor and excitor. Comparison of the results with the proposed method show that the latter is simpler in implementation because it is closed loop, does not require network reduction and also effective in terms of stabilization.

Test results on the multimachine system show that the control scheme is very effective in stabilizing the systems. With application of coordinated control scheme, the rotor angle variation with time is shown to become very low and velocity of faulted machine is shown to approach nearly zero. So these coordinated braking resistor and shunt reactor control and excitation control can be applied effectively to any power system to stabilize first swing and subsequent swing instability.

Basically, the control is determined at each instant by the conditions at that time and for the braking resistor and shunt reactor control, the control is inherently a bang-bang strategy. This will present some problems in realization of the controller. Multiple switching can occur when the trajectory approaches the switching boundary = 0 because of the variation of the switching boundary in the phase plane caused by varying L(t) and b(t). In addition, from the view point of voltage regulation, the excitation control can be excessive for smaller swings. Use of a deadband on the control action when the trajectory approaches the switching boundary or the origin of the phase plane can eliminate this. Another approach is to make the control action proportional to which was used here. The proportional control while not as effective as bang-bang control in the initial stages, provides a smooth transition to normal voltage regulation and for smaller swings, this control reduces to a velocity feedback. Proportional control seems to be preferable.

6.2 SUGGESTIONS FOR FURTHER RESEARCH

Further improvement on the multimachine system performance is possible at the cost of more complexity on the control scheme, such as including phase lead/lag compensators, governor and turbine control etc. Further areas of investigation includes the implementation of the control scheme on laboratory model of power system micromachines, etc. Simple measurement methods L(x) term in the control equation will definitely simplify implementation. Study of sensitivity of this term to parameters variation deserves attention.

While a highly detailed machine model may be used in the algorithm, the computational effort would be excessive for the benefit gained. A major objective of future studies is the consideration of various approximation in order to obtain a strategy that can be easily implemented by microprocessors or minicomputers. In this effort, a key factor is the choice of quantities to be measured in that they must be easily attained and locally measured. Some works with local instead of global control are encouraging.Last,not least, would be to study the control on some real systems; especially on the systems which are equipped with braking resistors and excitation system.

APPENDIX A

SYNCHRONOUS GENERATOR EQUATIONS

Park's equation relating the voltages,currents etc. for the development of the control strategy are given here. The symbols v,i,r,ψ and ω respectively denote the voltage,current,resistance,flux linkage and speed and the subscript d,q,a,f refer to direct axes,quadrature axes,armature and field quantities respectively. D denotes the differential operator d/dt.$2\pi f$ radian per second is chosen as the base speed ω_b.The speed of the machine is ω radian per second.

The voltages of the machine can be expressed as [45,47]

$$V_d = r_a(-i_d) + \frac{1}{\omega_b} D\psi_d - \frac{\omega}{\omega_b}\psi_q \quad (A.1.1)$$

$$V_q = r_a(-i_q) + \frac{1}{\omega_b} D\psi_q + \frac{\omega}{\omega_b}\psi_d \quad (A.1.2)$$

$$V_{fd} = r_{fd}\ i_{fd} + \frac{1}{\omega_b} D\psi_{fd} \quad (A.1.3)$$

$$V_{fq} = r_{fq}\ i_{fq} + \frac{1}{\omega_b} D\psi_{fq} \quad (A.1.4)$$

Negative signs are given to i_d and i_q since the aramature winding of a generator is an active network that converts mechanical energy into electric energy.

The flux linkages are expressed in terms of current and reactances as follows

$$\psi_d = x_d\ (-i_d) + x_{afd}\ i_{fd} \quad (A.2.1)$$

$$\psi_q = x_q\ (-i_q) + x_{afq}\ i_{fq} \quad (A.2.2)$$

$$\psi_{fd} = x_{afd}(-i_d) + x_{ffd}\ i_{fd} \quad (A.2.3)$$

$$\psi_{fq} = x_{afq}(-i_q) + x_{ffq}\ i_{fq}. \quad (A.2.4)$$

In the equations (A.2), the total reactances of the respective windings are denoted by x_d, x_q, x_{ff} and the mutual reactances of the respective axes by x_{afd} and x_{afq}.

Let some new voltages be defined as follows

$$E_{fd} = \frac{x_{afd}}{r_{fd}} v_{fd} \qquad (A.3.1)$$

$$E_q' = \frac{x_{afd}}{x_{ffd}} \Psi_{fd} \qquad (A.3.2)$$

$$E_d' = \frac{x_{afq}}{x_{ffq}} \Psi_{fq} \qquad (A.3.3)$$

$$E = x_{afd} i_{fd} \qquad (A.3.4)$$

Where, E_{fd}, E_q', E_d' and E are all internal voltages of the armature. E_{fd} may be interpreted as the field voltage as seen from the armature and v_{fd} is the voltage applied to the field winding of direct axis. E_q' is the q-axis transient internal voltage and E_{fd} equals E only in the steady state.

From (A.3.2) and (A.2) it can be derived,

$$E_q' = \frac{x_{afd}}{x_{ffd}} \Psi_{fd} = \frac{x_{afd}}{x_{ffd}} (x_{ffd}\ i_d - x_{afd}\ i_d)$$

$$= x_{afd} i_d - \frac{x^2_{afd}}{x_{ffd}} i_d$$

$$E_q' = x_{afd}\ i_d - (x_d - x_d')\ i_d \qquad (A.4)$$

where, x_d' is d-axis transient reactance which is defined as

$$x_d' = x_d - \frac{x^2_{afd}}{x_{ffd}} \qquad (A.5)$$

Similarly, $$x_q' = x_q - \frac{x^2_{afq}}{x_{ffq}}$$

From (A.4),

$$E_q = E_q' + (x_d - x_d') i_d$$

Similarly, (A.6)

$$E_d = E_d' - (x_q - x_q') i_q$$

Neglecting resistance and the transfer voltage (i.e. setting $D\Psi_d$, $D\Psi_q$, terms to zero) and considering the fact that the variation of frequency has little effect on voltage ($\omega / \omega_b = 1$), equation (A.1) and (A.2) can be combined as,

$$v_d = x_q i_q + E_d$$

$$v_q = -x_d i_d + E_q \qquad (A.7)$$

Combining equation (A.6) and (A.7) gives

$$v_d = x_q' i_q + E_d'$$

$$v_q = -x_d' i_d + E_q' \qquad (A.8)$$

Again, the field winding circuit time constant may be defined as,

$$T_{do}' = \frac{L_{FF} \text{ henry}}{R_F \text{ ohm}} = \frac{1}{\omega_b} \frac{x_{ffd}}{r_{fd}} \qquad (A.9)$$

APPENDIX B

SYSTEM DATA

B.1 Parameters for 4 - Machine System

a. Line Data

LINE		IMPEDENCE	
From	To	R	X
1	2	0.05	0.20
2	3	0.10	0.50
3	4	0.20	0.80
4	5	0.10	0.30
5	6	0.20	0.40
6	1	0.10	0.50

b. Synchronous Machine Data

Gen. No.	At Bus	Rating	H	x'_d	D(p.u)
1	1	100	95.3	0.004	0.00265
2	2	15	1.498	1.0	0.0318
3	3	40	2.997	0.50	0.0066
4	4	30	2.0	0.40	0.0016

c. Loads

Bus	P(MW)	Q(MVAR)
2	20.0	10.0
5	40.0	15.0
6	30.0	10.0

d. Load Flow for Prefault Condition

Bus	V	Ang(deg.)	P_G (MW)	Q_G (MVAR)	P_L (MW)	Q_L (MVAR)
1	1.0	0.0	33.2	9.1	0.0	0.0
2	1.002	-0.12	10.0	5.0	20.0	10.0
3	1.084	4.62	30.0	20.0	0.0	0.0
4	1.025	1.41	20.0	10.0	0.0	0.0
5	0.956	-2.80	0.0	0.0	40.0	15.0
6	0.953	-2.30	0.0	0.0	30.0	10.0

B.2 Parameters for 7 - Machine System

a.Line Data

LINE		IMPEDENCE		
From	To	R	X(p.u)	Y(p.u.)
2	3	0.04503	0.12365	0.10125
3	4	0.01185	0.07802	0.15185
4	0	0.01640	0.06518	0.15187
0	2	0.01639	0.06380	0.15187
3	1	0.00976	0.04839	0.10125
1	4	0.00976	0.04839	0.05060
4	5	0.00395	0.01975	0.10125
4	6	0.00751	0.01975	0.60760
3	9	0.01146	0.05530	0.10125
9	8	0.04880	0.19160	0.10125
8	7	0.01185	0.07402	0.15187
6	8	0.01876	0.06281	0.10125
4	9	0.04880	0.19160	0.10125

b.Synchronous Machine data

M/C at Bus	Rating	H	x'_d
1	100	11.35	0.074
2	100	7.75	0.118
3	100	14.31	0.062
4	100	17.98	0.049
5	100	11.35	0.074
6	100	12.76	0.071
7	100	10.71	0.087

c. Prefault Load Flow Condition

Bus	V	Ang(deg.)	P_G (MW)	Q_G (MVAR)	P_L (MW)	Q_L (MVAR)
2	1.0000	-6.2810	120.0	124.578	200.0	120.0
3	1.0400	-0.7920	256.0	100.335	0.0	0.0
4	1.0150	-2.9160	300.0	136.885	650.0	405.0
0	0.9894	-6.1310	0.0	0.000	90.0	45.0
1	1.0600	0.6560	217.0	95.109	0.0	0.0
5	1.0550	-0.8470	230.0	165.571	0.0	0.0
6	1.0200	-2.5090	160.0	39.286	80.0	30.0
9	0.9592	-5.7930	0.0	0.000	230.0	140.0
8	0.9909	-3.5090	0.0	0.000	100.0	50.0
7	1.0100	0.0000	175.1	47.177	90.0	40.0

B.3 Parameters for 11 - Machine System

a. Line Data

LINE			IMPEDENCE	
From	To	R	X(p.u)	Y-shunt(p.u)
KAPG	CHAN	0.0046	0.0177	0.0021
CHAN	MADA	0.0178	0.0677	0.0790
KAPG	MADA	0.0224	0.0855	0.0100
MADA	FENI	0.0564	0.2153	0.0253
SIKG	MADA	0.0093	0.0355	0.0042
MADA	KULS	0.0070	0.0266	0.0031
SIKG	HALI	0.0088	0.0337	0.0040
HALI	KULS	0.0112	0.0426	0.0050
KULS	BARU	0.0065	0.0248	0.0029
KAPG	BARU	0.0288	0.1100	0.0129
FENI	COMI	0.0281	0.1071	0.0126
COMI	ASMG	0.0333	0.1653	0.0180
ASMG	GHMG	0.0251	0.0958	0.0112
ASHG	GHHG	0.0066	0.0327	0.0328
ASMG	SHAG	0.0299	0.1142	0.0134
SIDG	GHMG	0.0255	0.0972	0.0114
GHHG	TONH	0.0040	0.0200	0.0200
MIRP	TONM	0.0084	0.0342	0.0035
POST	MIRP	0.0167	0.0684	0.0069
SIDG	POST	0.0135	0.0551	0.0056
SIDG	ULLO	0.0088	0.0361	0.0037

TONH	ISUH	0.0210	0.1042	0.1045
BHEG	FARI	0.0806	0.2380	0.0262
FARI	MPUR	0.0496	0.1465	0.0161
MPUR	BARI	0.0434	0.1282	0.0141
BARI	BAGE	0.0512	0.1512	0.0168
BAGE	GOAG	0.0333	0.0985	0.0099
GOAG	BHEG	0.1252	0.3698	0.0406
GOAG	NOAP	0.0174	0.0513	0.0056
NOAP	JESS	0.0198	0.0586	0.0064
JESS	JHEN	0.0347	0.1025	0.0113
JHEN	BATT	0.0355	0.0989	0.0109
BATT	BHEG	0.0174	0.0513	0.0056
BHEG	ISUM	0.0074	0.0220	0.0022
BOGG	ISUM	0.0788	0.2329	0.0235
ULLO	TONM	0.0112	0.0456	0.0048
SIDG	COMI	0.0508	0.1912	0.0334
ASMG	ASHG	0.0000	0.0600	0.0000
TONM	TONH	0.0000	0.0500	0.0000
GHMG	GHHG	0.0000	0.0600	0.0000
ISUM	ISUH	0.0000	0.0300	0.0000

b. Generator Data

M/C at Bus	Base MVA	H	X'_d
KAPG	100.0	11.361	0.1481
SIKG	100.0	3.6375	0.4658
ASMG	100.0	17.820	0.1021
SHAG	100.0	9.1325	0.2030

ASHG	100.0	12.160	0.1000
GHHG	100.0	5.1793	0.1659
SIDG	100.0	4.4062	0.3997
GHMG	100.0	6.0795	0.2399
GOAG	100.0	15.692	0.0945
BHEG	100.0	4.3200	0.3635
BOGG	100.0	5.6230	0.2186

c. Prefault Load Flow Condition

Bus	V	Ang(deg)	P_G (MW)	Q_G (MVAR)	P_L (MW)	Q_L (MVAR)
HALI	1.0810	-3.885	0.0	0.0	33.0	26.7
CHAN	1.0472	-2.864	0.0	0.0	44.7	33.5
MADA	1.0270	-3.488	0.0	0.0	14.1	10.6
KULS	1.0238	-3.566	0.0	0.0	25.6	19.2
FENI	0.9898	-3.928	0.0	0.0	42.5	31.9
COMI	0.9927	-3.057	0.0	0.0	86.2	63.8
POST	0.9988	-4.316	0.0	0.0	35.0	-57.6
MIRP	0.9864	-4.333	0.0	0.0	46.4	34.8
ULLO	0.9823	-4.194	0.0	0.0	98.3	73.7
TONM	0.9880	-3.958	0.0	0.0	84.8	60.8
TONH	1.0288	0.116	0.0	0.0	0.0	0.0
KAPG	1.0600	-2.375	155.0	121.226	0.0	0.0
SIKG	1.0250	-3.635	60.0	55.457	61.9	45.9
ASMG	1.0600	1.918	236.0	117.7	72.3	48.5
SHAG	1.0600	2.076	49.0	24.267	43.9	27.1

GHMG	1.0400	0.000	111.76	92.57	82.8	62.1
SIDG	0.9950	-3.518	74.0	54.0	104.2	78.1
GHHG	1.0450	1.123	210.0	151.69	0.0	0.0
ASHG	1.0700	3.075	294.0	130.0	0.0	0.0
BHEG	1.0450	-12.266	30.0	37.94	9.5	7.1
GOAG	0.9600	-16.897	98.0	84.341	89.4	67.1
BOGG	1.0550	-16.057	80.0	55.708	142.702	33.046
ISUH	0.9226	-7.6960	0.0	0.0	0.0	0.0
ISUM	1.0535	-11.775	0.0	0.0	105.2	78.9
FARI	0.9543	-16.298	0.0	0.0	15.1	11.3
MPUR	0.9226	-17.970	0.0	0.0	5.5	4.1
BARI	0.9020	-19.116	0.0	0.0	28.9	21.7
BAGE	0.9287	-18.187	0.0	0.0	14.1	9.2
NOAP	0.9530	-17.008	0.0	0.0	10.1	7.8
JESS	0.9514	-16.850	0.0	0.0	22.6	17.0
JHEN	0.9745	-15.496	0.0	0.0	18.8	14.1
BATT	1.0175	-13.452	0.0	0.0	9.2	6.9
BARU	1.0366	-3.6520	0.0	0.0	18.2	13.6

APPENDIX C

C.1. SUBROUTINE 1

```
C       THE FOLLOWING SUBROUTINE IS USED WITH THE INTERACTIVE POWER
C       SYSTEM ANALYSIS PACKAGE TO OBSERVE THE RESPONSE OF THE
C       UNSTABLE MACHINE APPLYING BRAKING RESISTOR & SHUNT
C       REACTOR CONTROL
C
        SUBROUTINE BCNTRL
        COMMON/OPT1/RF(20),XF(20),XAF(20),RK(20),RT(20),SL(20),EX(20)
        COMMON/OPT2/EN(20),A(20,60),CFD(20),DER(10),Y(10),W0,MOPT(20)
        COMMON/OPT3/NEQ(10),EREF(20),ZSD(20),ZSQ(20)
        COMMON/U2/KG,NR,NG,NM,KP,KO,IA,IG,IML,IPC,MAX1T,ITS,F,VA
        COMMON/BUS1/VKR(50),VKM(50),CKR(50),CKM(50),BUS(50)
        COMMON/G3/KBUS(20),KK(20),CD(20),CQ(20)
        COMMON/U5/JJ,LF,TSTEP,TIME,TMAX
        COMMON/U4/JSM,NRBUS,ANGMAX,NO,PINT,PINT2,PTM,IPRE,PRTIME,NOPT,SP41
        COMMON/DIF1/DEL(20),W(20),EF(20),PM(20)
        COMMON/DIF2/EQ(20),ED(20),ETTQ(20),ETTD(20)
        COMMON/G1/PT(20),QT(20),PE(20),H(20),DA(20),TQ(20),TD(20)
        COMMON/G2/XTD(20),XTQ(20),XSD(20),XSQ(20),RA(20)
        COMMON/QQ/UH(800),IH,DBF(800)
C
        PI=3.1415
        K=3
        UH(IH)=0.0
        UMAX=PM(K)-PE(K)
```

```
      UMIN=PM(K)-PE(K)-1.0
      UMAX=UMAX/(2.0*H(K))
      UMIN=UMIN/(2.0*H(K))
      X1=DEL(K)/W0
      X2=(W(K)-W0)/W0
C*******************************************
C     IF(X2.GT.0.0)GO TO 433
CCCCC IF(X2.LT.0.0)GO TO 533
C     IF(X2.LT.0.0.AND.UMAX.GT.0.0)GO TO 533
C     IF(X2.LT.0.0.AND.UMAX.LT.0.0)GO TO 633
C433  SIG=X1-0.5*X2**2/UMIN+PI/(2.0*W0)
C     GO TO 733
C533  SIG=X1-0.5*X2**2/UMAX-PI/(2.0*W0)
C     GO TO 733
C733  UH(IH)=0.0
C     IF(SIG.GT.0.0)UH(IH)=1.0
C     GO TO 833
C633  UH(IH)=0.0
C**********************************************
      SIG=X1-0.5*X2**2/UMIN+PI/(2.0*W0)
      IF(X2.LT.0.0)SIG =X1+0.5*X2**2/UMAX -PI/(2.0*W0)
      DBF(IH)=SIG
      UH(IH)=0.0
      IF(SIG.GT.0.0)UH(IH)=1.0
C     IF(TIME.GT.0.725)UH(IH)=0.0
C     WRITE(2,200)DEL(K),W(K),W0,UH(IH)
C200  FORMAT(5X,'DEL=',F10.5,5X,'WK=',F10.5,5X,'W0=',F10.5,'UH=',F5.2)
  833 WRITE(2,901)SIG,UH(IH),UMAX,X2,UMIN,X1
  901 FORMAT(2X,'SIG=',F10.5,3X,'UH=',F8.3,3X,'UMAX=',F10.5,'X2=',F10.5,
```

```
     1'UMIN=',F10.5,'X1='F10.5)5)
      IH=IH+1
C
  900 RETURN
      END
```

C.2. SUBROUTINE 2

```
C     THE FOLLOWING SUBROUTINE IS USED WITH THE INTERACTIVE POWER
C     SYSTEM ANALYSIS PACKAGE TO OBSERVE THE RESPONSE OF THE
C     UNSTABLE MACHINE APPLYING PROPOSED CO-ORDINATED
C     BRAKING RESISTOR-SHUNT REACTOR & EXCITATION CONTROL SCHEME.
C
      SUBROUTINE CONTRL(US,K)
      COMMON/OPT1/RF(20),XF(20),XAF(20),RK(20),RT(20),SL(20),EX(20)
      COMMON/OPT2/EN(20),A(20,60),CFD(20),DER(10),Y(10),W0,MOPT(20)
      COMMON/OPT3/NEQ(10),EREF(20),ZSD(20),ZSQ(20)
      COMMON/U2/KG,NR,NG,NM,KP,KO,IA,IG,IML,IPC,MAXIT,ITS,F,VA
      COMMON/BUS1/VKR(50),VKM(50),CKR(50),CKM(50),BUS(50)
      COMMON/G3/KBUS(20),KK(20),CD(20),CQ(20)
      COMMON/U5/JJ,LF,TSTEP,TIME,TMAX
      COMMON/U4/JSM,NRBUS,ANGMAX,NO,PINT,PINT2,PTM,IPRE,PRTIME,NOPT,SP41
      COMMON/DIF1/DEL(20),W(20),EF(20),PM(20)
      COMMON/DIF2/EQ(20),ED(20),ETTQ(20),ETTD(20)
      COMMON/G1/PT(20),QT(20),PE(20),H(20),DA(20),TQ(20),TD(20)
      COMMON/G2/XTD(20),XTQ(20),XSD(20),XSQ(20),RA(20)
      COMMON/SIGMA/S1,S2,S3,TFAULT,NMP
      US=0.0
```

```
IF(TIME.LE.TFAULT)GO TO 900
IF(MOPT(K).EQ.0) GO TO 900
IF(TSTEP.LE.1.E-5) GO TO 900
IF(K.EQ.NRBUS)GO TO 90
M=NRBUS
N=KBUS(K)
VR=VKR(N)
VM=VKM(N)
VK=SQRT(VR**2+VM**2)
ANK=ATAN2(VM,VR)
VR=VKR(M)
VM=VKM(N)
ANR=ATAN2(VM,VR)
VR=SQRT(VR**2+VM**2)
V1=EX(K)
V2=EN(K)
V3=EX(M)
V4=EN(M)
CLK=Y(K)*CFD(K)/(2.*H(K)*XTD(K)*TD(K))
CBK=-Y(K)/(2.*H(K)*XTD(K)*TD(K))
CLR=Y(M)*CFD(M)/(2.*H(M)*XTD(M)*TD(M))
CBR=-Y(M)/(2.*H(M)*XTD(M)*TD(M))
IF(CBK.GT.0..AND.CBR.GT.0.) GO TO 10
IF(CBK.LT.0..AND.CBR.LT.0.)GO TO 20
IF(CBK.GT.0..AND.CBR.LT.0.)GO TO 30
UMAX=CLK-CLR+CBK*V2-CBR*V4
UMIN=CLK-CLR+CBK*V1-CBR*V3
UKX=V2
UKN=V1
```

```
      URX=V4
      URN=V3
      GO TO 40
   10 UMAX=CLK-CLR+CBK*V1-CBR*V4
      UMIN=CLK-CLR+CBK*V2-CBR*V3
      UKX=V1
      UKN=V2
      URX=V4
      URN=V3
      GO TO 40
   20 UMAX=CLK-CLR+CBK*V2-CBR*V3
      UMIN=CLK-CLR+CBK*V1-CBR*V4
      UKX=V2
      UKN=V1
      URX=V3
      URN=V4
      GO TO 40
   30 UMAX=CLK-CLR+CBK*V1-CBR*V3
      UMIN=CLK-CLR+CBK*V2-CBR*V4
      UKX=V1
      UKN=V2
      URX=V3
      URN=V4
   40 X1=(DEL(K)-DEL(M))/W0
      CARD=X1
      X2=(W(K)-W(M))/W0
      X3=0.5*(PM(K)-PE(K))/H(K)-0.5*(PM(M)-PE(M))/H(M)
      IF(X1.GT.0.)GO TO 45
      UX=UMIN
```

```
      UN=UMAX
      UMAX=UX
      UMIN=UN
      X1=-X1
      X2=-X2
      X3=-X3
   45 SIG=X2-0.5*X3**2/UMIN
      IF(X3.LT.0.)SIG=X2-0.5*X3**2/UMAX
      ALPHA=UMIN
      IF(SIG.GT.0.)ALPHA=UMAX
      IF(ABS(ALPHA).LE.0.05)GO TO 85
      T1=3.1415927*0.5/W0
      SIG1=X1-T1-X2*X3/ALPHA+(X3**3)/(3.0*ALPHA**2)
      SIG2=SIG1+T1
      IF(SIG1.LE.0..AND.SIG2.GE.0.0)GO TO 50
      IF(SIG1.GT.0.)U=UMIN
      IF(SIG2.LT.0.)U=UMAX
      GO TO 60
   50 U=UMAX
      IF(SIG.GT.0.)U=UMIN
   60 CONTINUE
      IF(ABS(U-UMAX).LE.1.E-7)GO TO 70
      USK=UKN
      USR=URN
      IF(CARD.LT.0.)USK=-USK
      IF(CARD.LT.0.)USR=-USR
      GO TO 80
   70 USK=UKX
      USR=URX
```

```
      IF(CARD.LT.0.)USK=-USK
      IF(CARD.LT.0.)USR=-USR
   80 IF(ABS(U).LE..02)RETURN
      IF(SIG1.GT.0.)USK=S1*ABS(SIG1)*USK/ABS(USK)
      IF(SIG2.LT.0.)USK=S2*ABS(SIG2)*USK/ABS(USK)
      IF(SIG1.LE.0..AND.SIG2.GE.0.)USK=S3*ABS(SIG)*USK/ABS(USK)
      US=USK
      USMAX=100.*V1/RK(K)
      USMIN=100.*V2/RK(K)
      IF(US.GE.USMAX)US=USMAX
      IF(US.LE.USMIN)US=USMIN
      IF(PE(K).LT.0.0)US=USMAX
   85 X1=(DEL(K)-DEL(M))*180./3.1415927
      SACC=0.5*(PM(K)-PE(K))/H(K)
      WRITE(2,901)K,SIG1,SIG2,SIG,US,UMAX,UMIN,SACC,X2,X3
      RETURN
C     CONTROL FOR THE REFERENCE MACHINE
   90 CONTINUE
      CLK=Y(K)*CFD(K)/(2.*XTD(K)*TD(K)*H(K))
      CBK=-Y(K)/(2.*H(K)*XTD(K)*TD(K))
      UMAX=CLK+CBK*V1
      UMIN=CLK+CBK*V2
      IF(CBK.LT.0.)UMAX=CLK+CBK*V2
      IF(CBK.LT.0.)UMIN=CLK+CBK*V1
      EREF(1)=ANK
      X1=(DEL(K))/W0
      X2=(W(K)-W0)/W0
      X3=0.5*(PM(K)-PE(K))/H(K)
      SIG=X2-0.5*(X3**2)/UMIN
```

```
      IF(X3.LT.0.)SIG=X2-0.5*(X3**2)/UMAX
      ALPH=UMIN
      IF(SIG.GT.0.)ALPH=UMAX
      IF(ABS(ALPH).LE..05)GO TO 85
      SIG1=X1-3.1415927*0.5/W0-X2*X3/ALPH+(X3**3)/(3.0*ALPH**2)
      SIG1=SIG1-DEL(K-1)/W0
      SIG2=X1-X2*X3/ALPH+(X3**3)/(3.0*ALPH**2)-DEL(K-1)/W0
      IF(SIG1.GT.0.0)US=-S1*SIG1
      IF(SIG2.LT.0.0)US=-S2*SIG2
      IF(SIG1.LE.0..AND.SIG2.GE.0.)US=-S3*SIG
      US=-20.*SIG
      IF(CBK.LT.0.)US=-US
C  90 IF(SIG1.GT.0.)USR=200.*ABS(SIG1)*USR/ABS(USR)
C     IF(SIG2.LT.0.)USR=200.*ABS(SIG2)*USR/ABS(USR)
C     IF(SIG1.LT.0..AND.SIG2.GT.0.)USR=20.*ABS(SIG)*USR/ABS(USR)
C     USRMX=100.*V3/RK(M)
C     USRMN=100.*V4/RK(M)
C     IF(EREF(1).GE.USRMX)EREF(1)=USRMX
C     IF(EREF(1).LE.USRMN)EREF(1)=USRMN
C     P1=DEL(M)*180./3.1415927
C     SACC=0.5*(PM(M)-PE(M))/H(K)
C     WRITE(2,901)M,SIG1,SIG2,SIG,EREF(1),UMAX,UMIN,SACC,X2,X3
  900 RETURN
  901 FORMAT(5X,2HSW,2X,I2,3X,9F10.5)
    1 FORMAT(5X,1H*,2F10.5)
    2 FORMAT(5X,2H**,2F10.5)
    3 FORMAT(5X,3H***,2F10.5)
    4 FORMAT(5X,4H****,2F10.5)
      END
```

APPENDIX D

PONTRYAGIN'S MINIMUM PRINCIPLE

The control problem is to find an admissible control u^* that causes the system

$$\dot{x}(t) = a(x(t), u(t), t) \qquad (D.1)$$

to follow an admissible trajectory x^* that minimizes the performance measure

$$J(u) = \int_{t_0}^{t_f} g(x(t), u(t), t)dt \qquad (D.2)$$

Then a function called Hamiltonian [43] is defined as

$$H = g(x(t), u(t), t) + p^T(t)[a(x(t), u(t), t)] \qquad (D.3)$$

where $p_1(t), p_2(t), - - - - -$ are the Lagrange multipliers.

Pontryagin's minimum principle [43] states that an optimal control must minimize the Hamiltonian i.e. a necessary condition for u^* to minimize the functional J is

$$H(x^*(t),u^*(t),p^*(t),t) \leq H(x^*(t),u(t),p^*(t),t) \qquad (D.4)$$

for all admissible u(t) and for all $t \in (t_0, t_f)$, $p^*(t)$ is the optimal value of coestate p(t). Thus from Pontryagin's minimum principle, it is emphasized that $u^*(t)$ is a control that causes $H(x^*(t),u(t),p^*(t),t)$ to assume its global minimum.

REFERENCES

1. A.H.M.A. Rahim and D.A.H. Alamgir, 'A Closed-Loop Quasi-Optimal Dynamic Braking Resistor and Shunt Reactor Control Strategy for Transient Stability', Paper No.A.87 SM 496-3, Presented at IEEE/PES 1987 Summer Meeting, California, July 12-17, 1987.
2. E.W.Kimbark, "Power System Stability", Vol.1 and 111, John Wiley & Sons.
3. W.D. Stevension, "Elements of Power sSystem Analysis", 3rd Edition, McGraw-Hill Book Company, 1975.
4. R.H.Park, "Fast Turbine Valving", IEEE Transactions Power Apparatus and Systems, Vol.PAS-92, 1973, pp. 1065-1073..
5. J. Vandergrift and J.R.Woodall, "Fast Intercept Valving Aids Units Stability", Electrical World, 1970, pp.56-57.
6. R.H.Park, "Improved Reliability of Bulk Power Supply by Fast Load Control", Proc. of Amer. Power Conf., Vol.30, 1968, pp. 1128-1141.
7. F.P. de Mello, "The Effects of Control", IEEE Special Publication, 70M62, PWR, 1970.
8. R.H. Wedster et al., "Series Capacitor Switching to Quency Electromechanical Transients in Power Systems", IEEE Transactions Power Apparatus and Systems, Vol.PAS-90, 1971, pp.427-433.
9. O.J.M. Smith, "Power System control by Capacitor Switching" IEEE Transactions Power Apparatus and Systems, Vol. PAS-88, 1969, pp. 28-35.
10. E.W.Kimbark, "Improvement of System Stability by Switched

Systems, Vol. PAS-84, 1966, pp. 361-374.

11. O.J.M. Smith, "Optimal Transient Removal in a Power System", IEEE Transactions Power Apparatus and Systems, Vol.PAS-88, 1965, PP. 361-374.

12. N. Rama Rao and D.K. Reitan, "Improvement of Power System Transient Stability Using Optimal Control: Bang Bang Control of Reactance", IEEE Transactions Power Apparatus and Systems, Vol. PAS-89, pp. 975-984, May/June 1970.

13. S.M. Miniesy and E.V. Bohn, "Optimal Network Switching in Power Systems", IEEE Transactions Power Apparatus and Systems, Vol. PAS-90, No.5, pp. 2118-2123, Sept./Oct. 1971.

14. IEEE Working Group on Discrete Supplementary Controls of the Dynamic System Performance, "A Description of Discrete Supplementary Controls for Stability", IEEE/ASME/ASCE, Joint Power Generation conference, Buffalo, N.Y., Sept. 1976.

15. E.W.Kimbark, "Improvement of System Stability by Changes in Network", IEEE Transactions Power Apparatus and Systems, Vol. PAS-88, 1969, pp. 771-781.

16. J. Mesisel, "Dynamic and Transient Stability Augmentation", Engg. Foundation Conf., Henniker, N.H. August 1975.

17. Usman O. Aliu, "Corrective Control for Transient Emergency State of Power Systems", Ph.D. Thesis, Purdue University, Indiana, U.S.A. 1978.

18. D.Ye. Trofimenko, "The Stability of Hydro-electric Generator With Electric Braking", Electric Technology USSR, Vol.1, 1962, pp. 70-78.

19. V.M. Gornshtrin and Ya. N. Luginskii, "The Use of Repeated Electric Braking and Unloading to Improve The Stability of Power Systems", Electric Technology USSR, Vol.2, 1963, pp.292-302.

20. K.Yoshida et al., "Development of System Damping Resistor for Stabilization of Bulk Power Transmission", Elect. Engg. in Japan, Vol. 91, No.3, 1971, pp. 79-90.

21. H.M. Ellis et al., "Dynamic Stability of Peace River Transmission System", IEEE Transactions Power Apparatus and Systems, Vol. PAS-94, 1966, pp. 602-609.

22. R.G. Farmer et al., Four Corners Project Stability Studies", IEEE Paper 68-PC 7-8-PWR.

23. M.L. Shelton et al., "BPA 1400-MW Braking Resistor", IEEE Transactions Power Apparatus and Systems, Vol.PAS-94, 1975, pp. 602-609.

24. K. Nakamura and S. Muto, "Improvement of Power System Stability by Optimum Bang-Bang Control of Series Parallel Resistors", Elect. Engg. in Japan, Vol. 96, No.2, 1976, pp. 47-54.

25. A. Rahimi, "Dynamic Braking Control of Electrical Power Systems", IEEE PES Winter Meeting, N.Y., Paper No. A 78 299-0, 1978.

26. A. Sen and J. Meisel, "Transient Stability Augmentation with a Braking Resistor Using Optimal Aiming Strategies", Proc. IEEE, Vol. 125, No.11, pp. 1249-1255, November 1978.

27. K.K.Oey et al. "Dynamic Braking Strategies for Transient Stability Control to a Computer-Driven Micromachine", IEEE PES Winter Meeting, N.Y., Paper No. A 80 063-8, 1980.

28. C.S. Rao and T.K. Nag Sarkar, "half Wave Thyristor Controlled Dynamic Brake to Improve Transient Stability", IEEE PES Summer Meeting, Los Angeles, July 17-22, pp.1077-1083, 1983.

29. W.A. Mittelstadt, "Four Methods of Power System Damping", IEEE Transactions Power Apparatus and Systems, Vol. PAS-87, 1968, pp. 1323-1329.

30. Fei Yiqun et al., "A Microprocessor Based Optimal Quality Control of Dynamic Braking", Electric Power Research Institute, Beijing, China.

31. U.O. Aliyo and A.H. El-Abiad. "A local Control Strategy of Power Systems in Transient Emergency State, Part 1. Functional Design", IEEE Transactions Power Apparatus and Systems, Vol. PAS-101, pp. 4245-4253, 1982.

32. S.S. Joshi and D.G. Tamaskar, "Augmentation of Transient Stability Limit of A Power System by Automatic Multiple Application of Dynamic Brake", IEEE Transactions Power Apparatus and Systems, Vol.PAs-104, No.11, pp. 3004-3012, 1985.

33. T. Machida, "Improving the Transient Stability of A-C System by Joint Usage of D-C System", IEEE Transactions Power Apparatus and Systems, Vol. PAs-85, pp. 226-232, 1966.

34. A.E. Bryson and W.F. Denhem, "A Steepest Ascent Method for Solving Optimum Programming Problems", Trans. ASME, Ser. E, Vol. 29 Journal of Appl. Mech., pp. 247-257, 1962.

35. A.E. Bryson and W.F. Denhem, "Optimal Programming Problems with Inequality Constraints 11: Solution by Steepest Descent", A1AA J., Vol.2, pp.25-34, 1964.

36. R.F. Vachino, "Steepest Descent with Inequality Constraints on the Control Variable", J. SIAM Control, Vol.4, No.1, pp. 245-261, 1966.

37. A.H. EI-Abiad and K. Nagappan, "Transient Stability Regions of Multimachine Power systems", IEEE Transactions Power Apparatus and Systems, Vol. PAs-88, pp. 169-179, 1966.

38. R.H. Park, "Two-Reaction Theory of Synchronous Machines-II" AIEE, Vol. 52, pp. 352-354, 1933.

39. IEEE Committee Report, "Dynamic Models for Steam and

Hydroturbines in Power System Studies", IEEE Transactions Power Apparatus and systems, Vol.PAs-92, pp. 1904-1915, 1973.

40. IEEE Committee Report, "Exhibition System Models for Power system Studies" IEEE Transactions Power Apparatus and Systems, Vol. PAs-100, No.2, pp. 494-509, 1981.

41. P.M. Anderson and A.A. Foud, "Power System Control and Stability" The lowa State University Press, Ames, lowa, 1977.

42. M. Athans and P. Falb, "Optimal Control", McGraw-Hill, 1966.

43. D.E. Kirk, "Optimal Control Theory", Prentice Hall, 1970.

44. M.A. Pai, "Power System Stability Vol.3", North-Holland.

45. Y.N. Yu, "Electric Power system Dynamics", Academic Press, 1983.

46. S.M. Miniesy and E.V. Bohn, "Optimal Network Switching in Power Systems", IEEE Transactions Power Apparatus and Systems, Vol. PAS-90, No.5, pp. 2118-2123, Sept./Octo. 1971.

47. A.H.M.A. Rahim, l.M. El-Amin and D.H. Kelly, "Simple Quasioptimal Control of Excitation for Stabilization of Multimachine Power System", International Journal of Electric Power & Energy Systems, Vol. 3, No.4, pp. 208-214, Oct. 1981.

48. K.L. Lo, A.H.M.A. Rahimand S.K. Biswas, "Effects of Feedback Signals on the Transient Response of a Power System Using a Solid State Excitation System", Int. J. Electr. Engg. Educ. Vol 16, No. 1, pp. 79-86, 1979.

49. F.P. DeMello et al, "Practical Approaches to supplementary Stabilizing from Acceleration Power", IEEE Transactions Power Apparatus and Systems, Vol. PAS-97, No.5, pp. 1515-1522, Sept./Oct. 1978.

50. J.P. Bayne et al, "Static Exciter Control to Improving Transient Stability", IEEE Transactions Power Apparatus

and Systems, Vol. PAs-94, No.4, pp. 1141-1146, July/August 1975.

51. Yau-nan Yu and C. Siggers, "Stabilization and Optimal Control Signals for Power System", IEEE Transactions Power Apparatus and Systems, Vol. PAs-90, No.4, pp. 1469-1481, July/August 1971.

52. C. Concordia, "Steady-state Stability of Synchronous Machines as affected by voltage regulator characteristics, AIEE Transactions Power Apparatus and Systems, Vol.PAS-63, pp. 215-220, 1944.

53. M.S. Dyrkacz, C.C. Yound and F.J. Maginniss, "A digital transient stability Program Including The Effects of Regulator, Exciter and Governor Response", AIEE Transactions Power Apparatus and Systems, Vol. PAS-79, pp. 1245-1257, 1960.

54. F.P. DeMello, D.N. Ewart, M. Temoshok, "Stability of Synchronous Machines as Affected By Excittation Systems, Machine and System Parameters", Proceedings American Power Conference, Vol. XXVII, PP 1150-1159, 1965.

55. P.L. Dandeno, A.N. Karas, K.R. McClymont and W. Watson, "Effect of High Speed Rectifier Excitation Systems on Generator Stability Limits" IEEE Transactions Power Apparatus and Systems, Vol.PAS-87, pp. 190-201, January 1968.

56. F.R. Schlief, H.D. Hunkins, G.E. Martin and E.E. Hattan, "Excitation Control to Improve Power Line Stability", IEEE Transactions Power Apparatus and Systems, Vol. PAs-87, pp. 1426-1434, June 1968.

57. F.R. Schief, H.D. Hunkins, E.E. Hatton and W.B. Gish "Control of Rotating Exciters for Power System Damping: Pilot Application and Experience", IEEE Transactions Power Apparatus and Systems, Vol. PAs-88, pp. 1259-1266, 1969.

58. F.P. DeMells and C. Concordia, "Concepts of Synchronous Machine Stability as Affected by Excitation Control", IEEE Transactions Power apparatus and Systems, Vol. PAs-88, pp. 316-329, 1969.

59. M.V. Rao and M.P. Dave, "Non-linear Excitation Stabilizer for a Synchronous Machine over Wide Range Operating Conditions", Paper No. A.76 139-1976, Presented at IEEE PES Winter Meeting, New York, 1976.

60. M.V. Rao and M.P. Dave, "Stabilization of Multimachine Systems Through Non-linear Gain Excitation Control, Paper No. A.77, 088-8, Presented at IEEE PES Winter Meeting, New York, 1977.

61. D.G. Ramey, R.T. Byerly and D.E. Sherman, "The Application of Transfer Admittance to the Analysis of Power System Stability", IEEE Transaction Power Apparatus and Systems, Vol.PAs-90, pp. 993-1000, 1971.

62. R.D. Masiollo, F.C. Schweppe, "Multimachine Excitation Stabilization Via System Identification", IEEE Transactions Power Apparatus and Systems, Vol. PAs-94, No.2, pp. 444-452, 1975.

63. O.P. Malik, G.S. Hope and A.A.H. El. Ghanadkly, "Online Adaptive Control of Synchronous Machine Excitation", Proceedings of IEEE PICA Conference Toronto, pp. 59-57, 1977.

64. M.A.H. Sheirah, G.S. Hope, O.P. Malik, "Self-Tuning Voltage and Speed Regulators for a Generating Unit", Proceedings of IEEE/ASME/ASCE Joint Power Conference, Dallas, TX,1978.

65. G. Ledwich, "Adaptive Excitation Control", Proceedings IEEE 1979, paper no. A.79. 126-3, pp. 249-253.

66. G.T. Hydt and Daozhi Xia, "Self-Tuning Controller for Generator Excitation Control", IEEE Transactions Power Apparatus and Systems, Vol. PAs-102, June 1983.

67. A. Yan, M.D. Woong and Yao-nan-Yu, "Excitation Control of

Torsional Oscillations", paper no. A79.505-9, IEEE PES Summer Meeting, Vancouver, July 1979.

68. Yao-Nan Yu and Andrew Yan, "Multi-Mode Stabilization of Torsional Oscillations Using Feedback Control", IEEE Transactions Power Apparatus and Systems, Vol. PAs-101, pp. 1245-1253, May 1982.

69. H.A.M. Mousa and Yao-nan Yu, "Optimal Power System Stabilization through Excitation and/or Governor Control, IEEE Transactions. Power Apparatus and Systems, Vol. PAs-91, pp. 1166-1174, 1972.

70. A.R. Doraiswami, A.M. Sharaf and J.C. Castro, "A Novel Excitation Control Design for Multi-machine Power Systems", IEEE Transactions Power Apparatus and Systems, Vol. PAs-103, pp. 1052-1058, 1984.

71. J.Y.H. Chen and G.L. Kusic, "Dynamic Stability and Excitation Control of Directly Coupled Multimachine Systems", IEEE Transactions Power Apparatus and Systems, Vol. PAs-1-3, pp. 389-397, 1984.