DECENTRALIZED CONTROLLERS FOR INTERCONNECTED POWER SYSTEMS

A Thesis

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by

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ABSTRACT

This thesis presents the results of studies carried out into problems associated with the provision of auxiliary damping of electromechanical oscillations in a multi-machine electrical power system. A particular real power system comprised of five generating plants and an infinite bus was investigated in these studies.

A review is given of the approaches used at present to improve system damping using power system stabilizers and alternative approaches utilizing modern control system theory are proposed.

The procedures followed in the mathematical modelling of the various power system components are given in detail and the digital computer-simulation of the system under study is described.

Two specific approaches to power system stabilizer design, on a linearized-system basis, are presented. The first leads to a centralized controller which depends for its operation on the exchange of data between the central controller and each of the plants. Simulation studies indicate that this control approach could give good results but it is unsatisfactory because of its absolute reliance upon sound telemetery channels. The second approach leads to localized controllers, one at each plant, without the need for data exchange between the plants or with the plants and the central control device. Simulation studies indicate that this could offer a viable alternative to the schemes which are in use at the present time for power system stabilization.

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PRINCIPAL SYMBOLS

Suffices a, d, q, f, k	armature, d-axis, q-axis, field, and damper windings.
Subscript i	refers to the i^{th} machine or the i^{th} component.
V, I	terminal voltage and current of a machine (in p.u.)
v, i	armature voltage and current refered to the machine reference frame (in p.u.)
V_{ref}	reference input voltage to an exciter (in p.u.)
E'_q	voltage proportional to the field flux linkages (in p.u.).
E_f	field voltage (in p.u.)
δ_i	rotor angle measured between the q-axis of the i^{th} machine and the infinite bus voltage (in rad).
P_{ei}	electrical output power of i^{th} machine (in p.u.).
D_i	machine or plant damping factor.
H_i	inertia constant of the i^{th} machine (in seconds).
T'_{do}	open circuit d-axis transient time constant (in seconds).
X_{fd}, X_ℓ	field d-axis windings mutual and leakage reactances (in p.u.).
X_d, X'_d	d-axis synchronous and transient reactances (in p.u.)
ω_o	synchronous speed (377 rad/sec).
ω_i	rotor speed of the i^{th} machine (rad/sec).
S	Laplaces operator or saturation function.
X	machine reactance or state vector of the system.

PRINCIPAL SYMBOLS (Cont.)

L_{AD}	is the magnetizing inductance in the d-axis equivalent circuit of a synchronous machine.
$[\ ]^T$	transpose of $[\ ]$.
$\mathrm{Re}\{\ \}$	is the real part of $\{\ \}$.
$[\ ]^{-1}$	denotes the inverse of $[\ ]$.
Prefix Δ	indicates small changes.
Subscript o	indicates operating point value.
Superscript -	denotes phasor.
Superscript *	denotes complex conjugate.
$\|(\cdot)\|_E$	the Euclidean norm of the matrix $(\cdot)$, which is the square root of the sum of the squares of the elements of $(\cdot)$.
$\rho(\cdot)$	the spectral radius of $(\cdot)$ i.e. the eigenvalue of $(\cdot)$ having the largest absolute value.
$\mathrm{tr}(\cdot)$	the trace of $(\cdot)$ i.e. the sum of its diagonal elements.

1. INTRODUCTION

1.1 Objectives of the Project

The main aim of the work presented in this thesis was to introduce a new technique to solve the stabilization problem facing a real multi-machine power system.

At the present time, power system stabilization is achieved through local phase-compensation stabilizers. The stabilizer counteracts the negative damping arising from excitation system dynamics. It acts to compensate for the phase lags through the generator, excitation systems, and power system such that the stabilizer path provides torque changes which are in phase with speed changes.

Although this is the most widely used straightforward approach, easily understood and implemented in the field, stabilizers based on this technique are hard to tune in large systems and they may contribute negative damping due to their interaction with the torsional oscillations.

More recently, several researchers have investigated the use of optimal control techniques, which utilize a state-space representation and calculate a gain matrix which, when applied as a multivariable feed-back controller, will minimize an objective function. This thesis presents an extension to these techniques whereby static decentralized feedback controllers have been designed to stabilize a power system. These controllers are non-dynamic so that no torsional interaction will take place, also they have low gains so that they are applicable at low cost and with high reliability.

1.2 Outline of the Thesis

In this first chapter, a brief statement of the power system stabilization problem is given.

Chapter 2 presents the steps followed in preparing a multi-machine power system model for dynamic simulation tests. These tests are required to investigate the dynamic interaction between the power plants in response to an impact in the power network.

Chapter 3 discusses the test results and identifies what type of instability problems the system has. Also it gives the first step towards the solution by formulating the system components in the state-space form.

Chapter 4 mainly deals with a technique used to solve the problem. The technique describes a method to design a centralized stabilizer for the multi-machine system. The effectiveness of this stabilizer was tested by simulating the system under the same impact.

In Chapter 5 an alternative solution to the problem is demonstrated. This solution was achieved using an approach based on Decentralized controllers, the effectiveness of which was checked through simulation.

Finally, a summary of the work done and the conclusions reached are presented. Appendices A.1 and A.2 have been included to provide a ready reference for background information on the sources of negative damping in power systems and on some of the available techniques that deal with this problem.

1.3 Power System Stability and Damping

Stability is still one of the major problems facing power system operation. The power system is normally in a dynamic balanced state, i.e. the mechanical power input of each generator is in balance with the sum of the losses and the electrical power output of that generator at a specified operating point. However, if the equilibrium state is lost due to one or a combination of the following reasons:

1. Lightning
2. Faults or short circuits
3. Open circuits
4. Switching
5. Loss of a large load,

a transient that causes the rotors of the synchronous machines to "swing" will occur. This is because the net accelerating (or decelerating) torques are exerted on these rotors, and if these torques are sufficiently large, rotors may swing far enough so that one or more machines "slip a pole", and synchronism is lost. The purpose of the material presented in this chapter is to describe dynamic stability phenomena briefly .

Stability in general can be classified into two categories; namely, transient oscillatory stability and dynamic stability.

1.3.1 Transient oscillatory stability

If there is any change in the power network-configuration, the input impedance seen by each plant may be much different than that existing prior to the change. Such changes cause the machine terminal voltage, rotor angle and frequency to change. Following a disturbance of this nature the airgap flux will change due to:

a) the sudden change in the armature currents which induce currents in the damper windings and in the rotating mass. The induced currents usually decay with a time constant $T''_d \simeq T''_q < 0.10$ seconds and are referred to as "subtransient" actions,

b) the induced currents in the field winding due to the sudden changes in the armature currents. This transient usually decays with a time constant of several seconds, e.g. $T'_d \simeq 2.0$ seconds and are referred to as "transient" actions.

When a disturbance takes place in a power system, the electromagnetic field energy stored in the gap of each generating unit will change accordingly in a very short time of several micro seconds and the excitation system will react to cover the error in the induced E.M.F. If the electromagnetic field energy is not sufficient to cover the error, the generating unit will provide (or absorb) power from the kinetic energy stored in the rotating mass within a time of several seconds and consequently the governor system will react to compensate the resulting difference in the stored energy as indicated by system frequency. If the disturbance is sustained for a relatively long time, the control system of the boiler will react to provide the required energy and if all systems fail, the unit will be isolated by the action of the protective system.

1.3.2 Dynamic oscillation and stability [1, 2, 3]

When the output power of a unit in a power system is gradually changed, due to any reason, low frequency oscillations of a machine rotor will tend to occur around its operating point. The frequency of these oscillations is mainly characterized by the inertia time constant of the machine ($\tau = 2H$) and by its synchronizing coefficient, K_1. Since τ has a fixed value and K_1 is a function of the operating point, then K_1 plays an important role in the dynamic response of the generating unit.

Dynamic oscillations can be classified into two types; namely, "local mode" and "inter area mode" oscillations.

a) Local mode oscillations

Local mode oscillations occur when a generating unit (or the equivalent generating unit) is swinging with respect to the rest of the system. Spontaneous local oscillations tend to occur when the generating unit has a relatively low steady state stability limit such as for an isolated power station. This mode normally has a characteristic frequency range of (1-3) Hz depending mainly on the synchronizing coefficient.

b) Inter area mode oscillations

Inter area mode oscillations occur when multi-power stations in a system (or their equivalent generating units) are swinging with respect to each other or against machines in another part of the system. Analysis of inter-area modes is more difficult because of the complexity of the transmission system and the consideration of the interaction between the individual power stations. The characteristic frequency of this type is generally less than 0.7 Hz which is lower than that of the local mode, because of the higher combined inertia of large groups of machines, and the higher effective reactance of tie-lines between these large groups. Most oscillation modes among generators are positively damped and the natural damping of the system represented by the positive damping coefficient ("D") will prevent any sustained oscillations unless a source of negative damping is introduced.

> Negative damping [1, 2, 3,] can be introduced to a power system from several sources, the most common of which are voltage regulators and exciters, high inertias and speed controllers.

These aspects have been well documented in the literature . They have been summarized for convenient reference in Appendix A.1 of this thesis.

1.4 Stability Improvement

Although several methods to improve transient stability are available [4], few of them have been used for practical reasons. Some of these methods are:

a) Braking resistors.
b) Generator dropping.
c) Load shedding.
d) Switched series capacitors.
e) Switched shunt reactors or capacitors.
f) Reducing the clearing angle through high speed protective system.
g) Building stronger interties.

The choice of any one or combination of these methods is made on the basis of economic considerations in each specific system case. To improve dynamic stability, the number of methods are limited to a few.

To offset the introduced phase lag and to improve the overall system damping, artificial means of producing torques in phase with the speed are introduced. These are called "Power System Stabilizers" (PSS). With power system stabilizers (PSS) stabilizing signals are introduced in excitation systems at the summing junction, as shown in Figure 1.1, where the reference voltage and the signal produced from the terminal voltage are added to obtain the error signal fed to the regulator-exciter system.

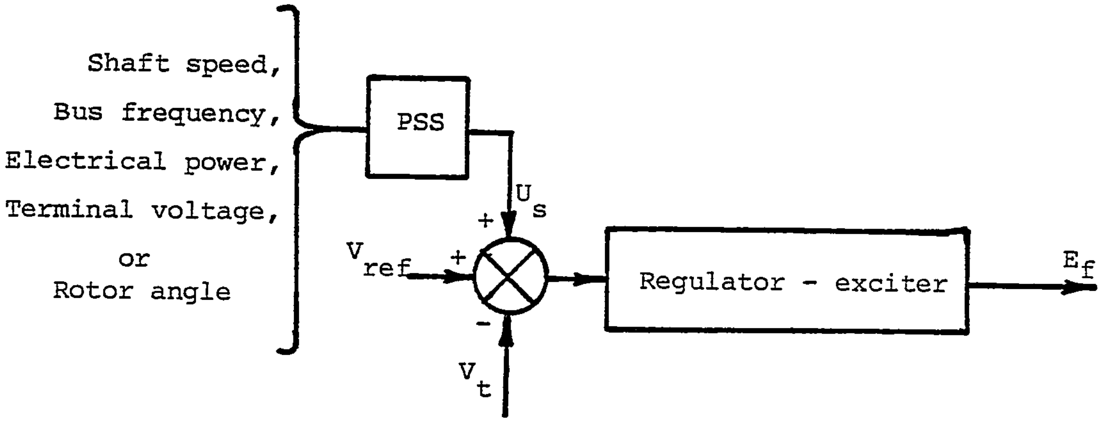

Figure 1.1: PSS implementation.

The input signal to this PSS could be one or a combination of deviations in various variables, measured at the output terminals of the generating unit, as shown in Figure 1.1.

Basically there are three major alternative stabilization procedures to improve dynamic stability. They are

a) Stabilization for non-linear systems (empirical approach).

b) Stabilization for linear systems (classical approach).

c) Stabilization for linear systems using pole placement.

These methods have been documented in the literature [7, 8, 9, 10]. For reference, the methods have been summarized in Appendix A.2 of this thesis.

1.5 Summary

In this chapter the background to the development of the dynamic stability and the sources of negative damping in power systems have been briefly stated. Also the concept of stabilization of linear time-invariant multivariable models of a power system with power system stabilizer is introduced. In later sections of this thesis it is shown how the simple PSS concept can be extended on a multi-variable basis to provide overall improved system damping.

In the next chapter, a real large interconnected multi-machine power system is described and the steps taken to prepare a model of it for dynamic simulation tests are given.

2. PREPARATION OF A REAL MULTI-MACHINE POWER SYSTEM MODEL FOR DYNAMIC STABILITY STUDIES

2.1 Introduction

This chapter deals with the techniques used in preparing the power system model for dynamic-interaction investigation. This is typical for any study of this type.

Dynamic stability studies can be considered as an extension of the techniques employed for the first swing transient stability, to include more detailed representations for the synchronous machines and their controllers.

In the studies reported in this thesis no attention has been given to either the turbines and their governors or to the boilers. This is due to the relatively long time constants associated with their mechanisms. Also, in considering the excitation systems as the only auxiliaries for damping of oscillations of the generating units, provides a margin of safety since, in fact, some damping will be provided by the prime movers and their associated controllers.

2.2 Real Power System Configuration

Figure 2.1 shows a single line diagram of the 30 KV multi-machine real interconnected power system which was studied.* This system is linked to another, relatively

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*Private Communication (Electricity Corporation of Benghazi, Libya).

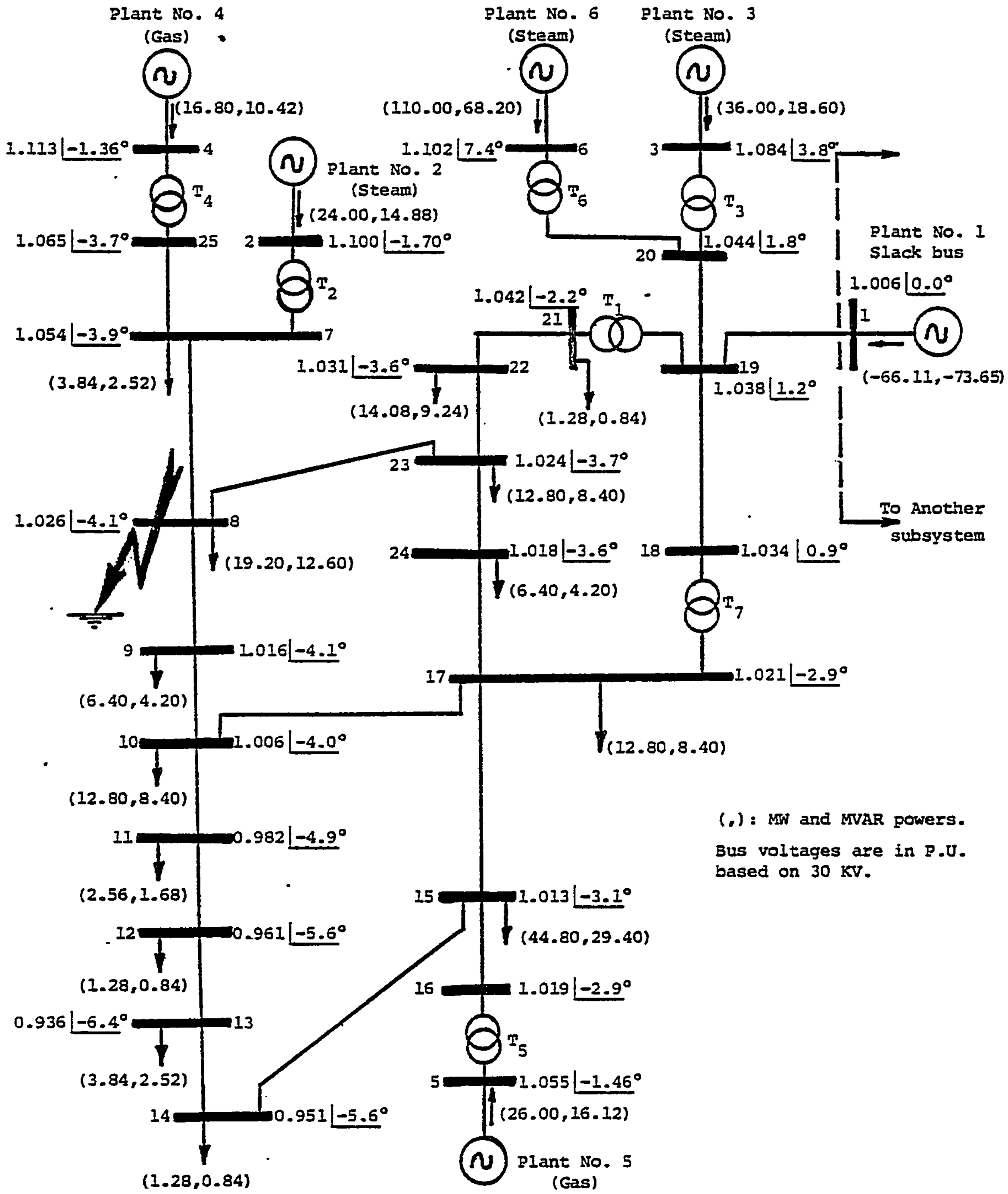

Figure 2.1: Five plants/infinite bus 30 KV real power system.

large subsystem, bus 1, through 220 KV overhead transmission lines. Most of the power delivered to the loads (8 → 14) must come through the double-circuit underground cable (7-8) (see load flow results) which runs through a salty soil area. The problem of instability is raised by two factors;

i) the corrosion effect on the cable (7-8) at the jointed-terminals, and

ii) weakness in the insulation-strength between the cores of the cable (7-8), due to heavy copper-loss dissipated as a heat. Although, the first factor can be overcome, the second one becomes a serious problem as the power demand increases. The obvious solution, cable replacement with a higher power cable is costly. Plants number 2, 3, 4 and 5 each consist of a number of small identical generating units which are represented by a single equivalent unit which has an equivalent inertia constant given by

$$H_{eq} = \frac{\prod_{i=1}^{n} H_i}{\sum_{\substack{i=1 \\ j=1 \\ i \neq j}}^{n,n} H_i H_j}$$

where n is the number of units operating in parallel.

Plant No. 1 is an infinite bus, at which the voltage and the frequency are constant and taken as a reference for the variables at the other plants.

Plant No. 6 is a steam turbine hydrogen cooled single generating unit with a full load capacity of 150 MVA/13.8 KV, 0.8 PF and an inertia of 2.80 secs. This sixth unit is to be added to the system and its effects are the subject of this study.

2.3 Representation of Power System Components

Power components like machines, transmission system and exciters should be modeled properly to achieve a reasonable accuracy in simulation tests.

2.3.1 Synchronous generator model

Figure 2.2 shows a block diagram for a synchronous machine connected to an external network.

This type of modelling was adopted by R. Podmore [16], in which saliency is considered by representing the machine in both d-axis and q-axis, also the effect of the saturation on the airgap voltage, E_{at} , has been considered as well. Moreover, the current-components at the machine terminals are transformed from the network reference frame to the machine reference frame through the operation represented by $T(\delta)$.

2.3.2 Excitation system model

There are several models for excitation systems. The complexity of which depends upon the degree of accuracy

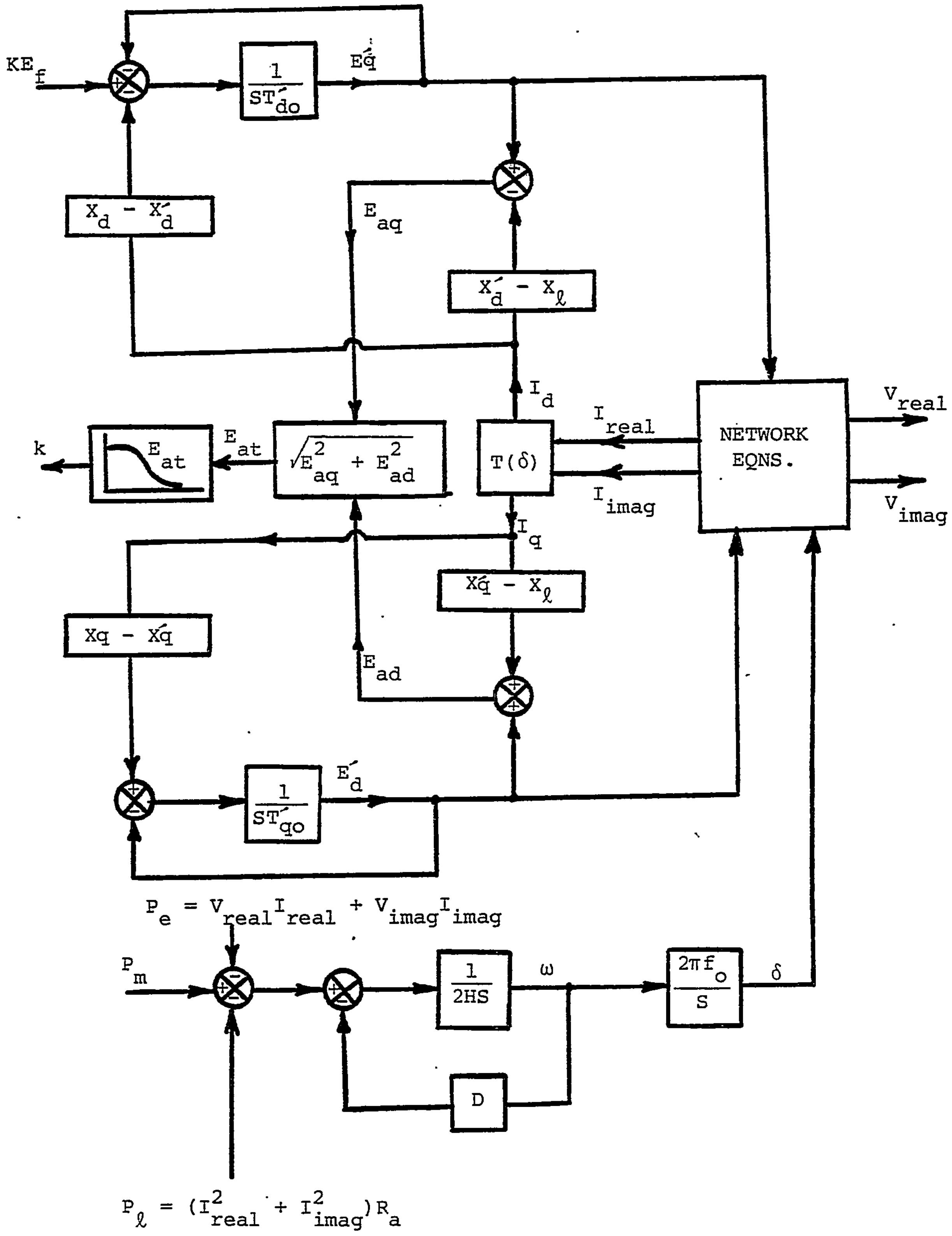

Figure 2.2 : Synchronous Generator Model.

required; however, in this case, all the power plants, of the system shown in Figure 2.1 are equipped with rotating type excitation systems represented by IEEE type 1, shown by the block diagram in Figure 2.3. In this figure the error in the terminal voltage of the machine is fed to the amplifier, through the limiter to the exciter and then to the field winding.

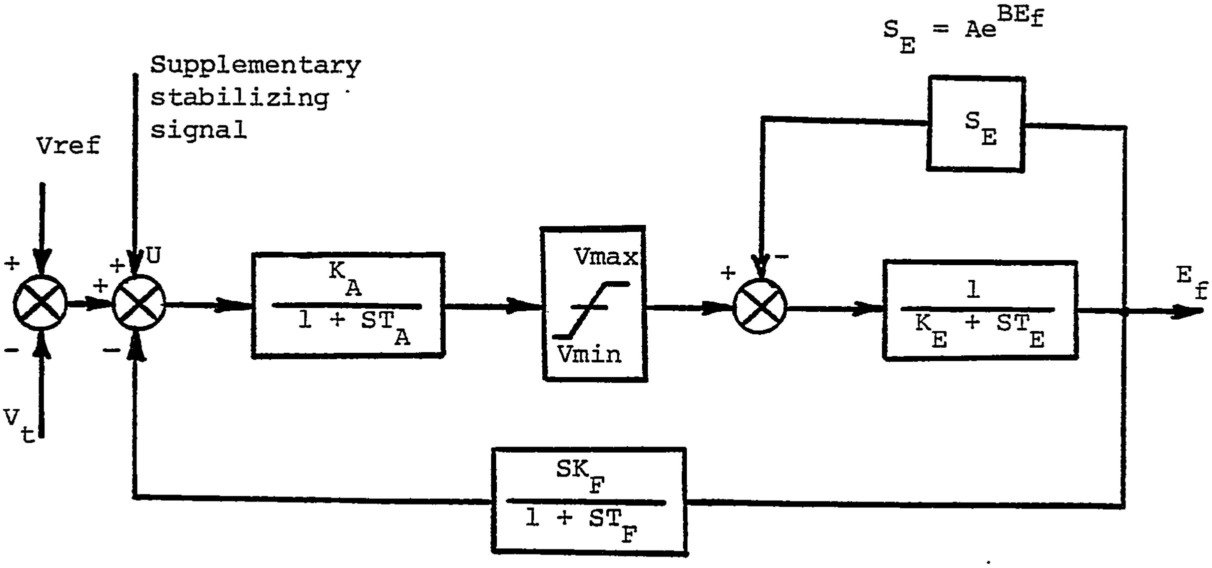

Figure 2.3: IEEE Type 1 rotating excitation system Model

The function of the limiter in the excitation system, is to prevent overheating of the field winding, in the case of excessive error signals. Also the lower limit is sometimes used to insure against loss of synchronism due to insufficient excitation. Moreover, Figure 2.3 shows the junction point at which a supplementary signal may be added.

The saturated reactances of a synchronous machine are smaller than the unsaturated ones, and the stability limit computed with saturation neglected and the excitation voltage assumed constant is smaller than the true stability limit with saturation present and constant field voltage. Hence saturation phenomenon plays an important role in determining stability behavior of the synchronous machines.

2.4 Determination of a Saturation Function for a Synchronous Machine [2]

The flux linking each circuit in the stator windings depends upon the exciter output voltage, the loading of the magnetic circuit (saturation), and the current in the different windings. Figures 2.4. a, b and c show how the airgap voltages, ν_d and ν_q, could be effected by the amount of the saturation in the coupling magnetizing inductances L_{AD} and L_{AQ} . Since the q-axis inductance L_{AQ} seldom saturates, it is usually necessary to adjust only L_{AD} for saturation.

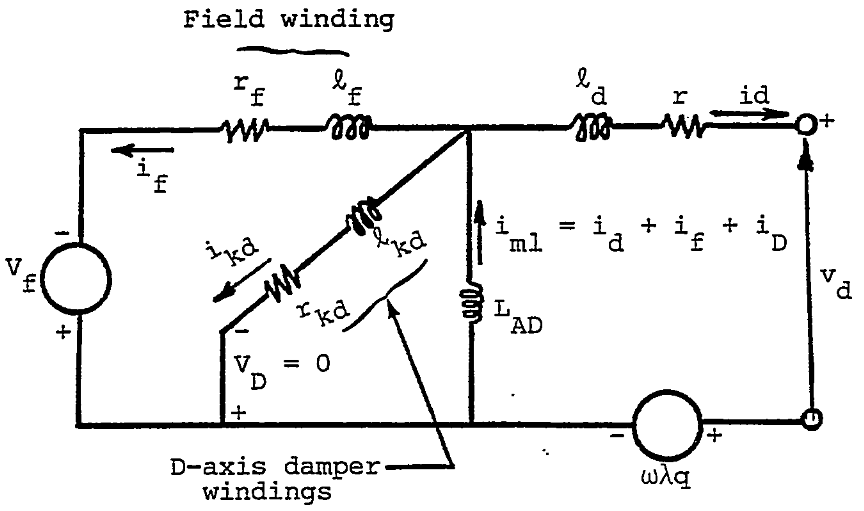

Figure 2.4(a): Direct axis equivalent circuit of a synchronous machine.

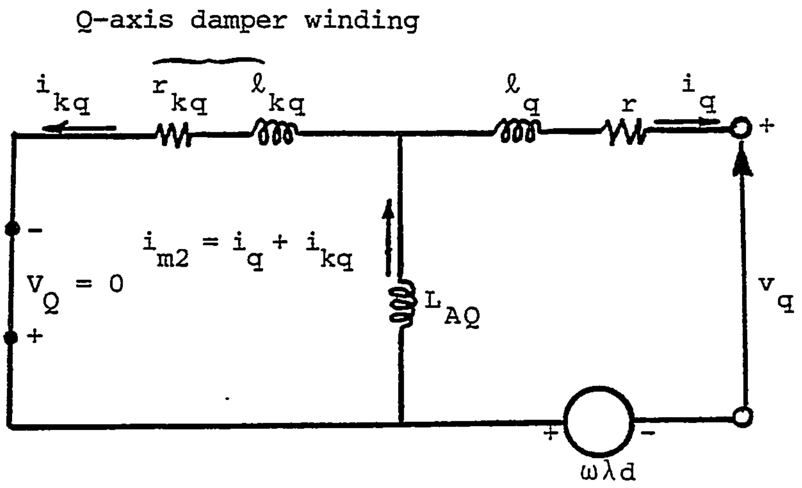

Figure 2.4(b): Quadrature axis equivalent circuit of a synchronous machine.

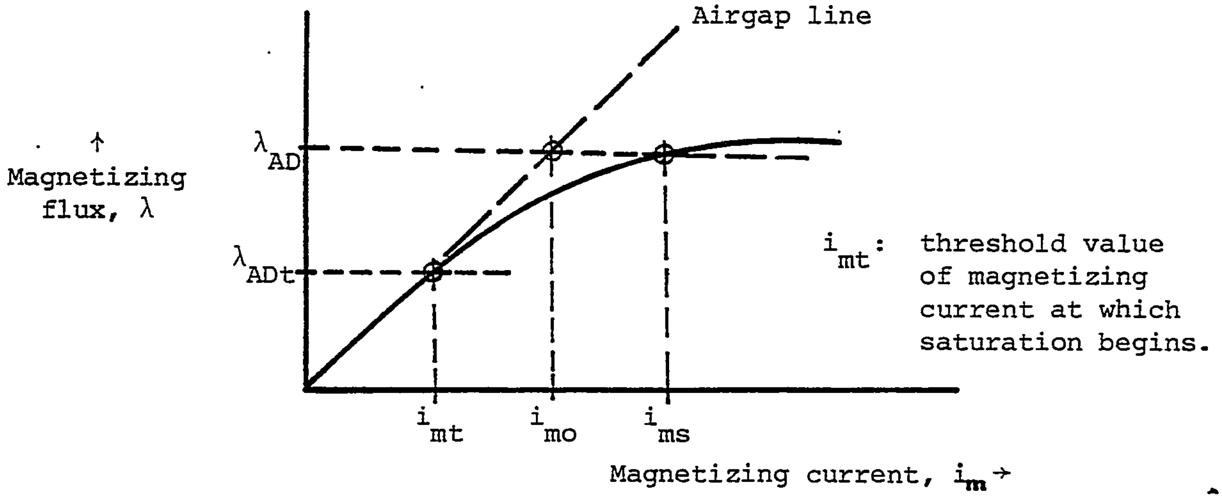

Figure 2.4(C): Open circuit saturation curve for λ_{AD}.

At any value of magnetizing flux λ_{AD}, saturation factor K is defined as

$$K \triangleq \frac{i_{mo}}{i_{ms}} \tag{2.2}$$

The current increment needed to satisfy saturation is

$$\Delta i_m \triangleq i_{ms} - i_{mo} ,$$

and for a flux linkages greater than λ_{ADt}, the current increment, Δi_m, increases exponentially following an approximate relation given by

$$\Delta i_m = A \exp[B(\lambda_{AD} - \lambda_{ADt})] , \quad \lambda_{AD} > \lambda_{ADt} \tag{2.3a}$$

Equation (2.3) can be rewritten in terms of the open circuit terminal voltage, E_a, as follows;

$$S \triangleq A\, e^{B \cdot E_a} . \tag{2.3b}$$

where

S is the saturation function.

The obtained data for Plant No. 6 were plotted as shown in Figure 2.5 from which, the saturation can be evaluated at two points on the curve,

$$S_{11} = \frac{700 - 680}{680}$$

$$= 0.02941$$

$$S_{14} = \frac{960 - 865}{865}$$

$$= 0.10983$$

thus $$B = \ln(S_{11}/S_{14})/(E_{a11} - E_{a14})$$

$$= \ln(\frac{0.10983}{0.02941})/(14 - 11) * 10^3 = 0.43920 \times 10^{-3}$$