THE UNIVERSITY OF MANITOBA

SOME APPLICATIONS OF PARAMETER ADAPTIVE TECHNIQUES IN POWER SYSTEM CONTROL

by

YOUSSEF LOTFY ABDEL-MAGID

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements for the Degree
of Doctor of Philosophy

DEPARTMENT OF ELECTRICAL ENGINEERING

WINNIPEG, MANITOBA R3T 2N2

February 1976

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To my parents .....

For many years of encouragements.

To my wife .....

For the understanding and support
that permit a thesis to be done.

ABSTRACT

The purpose of the research described herein was to investigate the possibility of applying parameter adaptive control techniques to the design of power system controllers in order to eliminate some of the compromise normally involved in the design of these controllers. Two different power system problems were considered, and in each case a different adaptive technique was suggested.

The first problem deals with the design of adaptive stabilizers to supplement generator static excitation systems. Eigen-value techniques were used to determine the influence of the generator static excitation on its small perturbation stability for a wide range of loading. A variable structure power stabilizer that will adapt to changes in system dynamics caused by load changes was then synthesized in such a way as to make the overall system optimum with respect to a prescribed criterion. A direct approach to the problem was taken, employing the state-space point of view and an open-loop adaptive technique based on measurements of the system operating conditions. Analog computer tests showed the effectiveness of the variable structure power stabilizer.

The second problem deals with the variation of incremental speed deviation with loading. A closed-loop adaptive controller was introduced to compensate for these variations.

Computer simulations showed that the adaptive loop is capable of maintaining satisfactory performance.

ACKNOWLEDGEMENTS

The author wishes to express his deep gratitude to Professor Glen W. Swift for suggesting the research area as well as for his valuable guidance, supervision and encouragement during the course of this research. The author is also indebted to Professor Swift for reading the thesis and offering many helpful suggestions for its improvement.

The financial support provided by the University of Manitoba, the National Research Council of Canada and Manitoba Hydro is greatly appreciated.

The author also wishes to thank his colleagues and staff members of the Department of Electrical Engineering for their cooperation. Special appreciation is due to Mrs. Shirley Clubine for her untiring effort in expertly typing the thesis.

Above all, the author acknowledges the faithful patience and constant encouragement of his wife, Azza.

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LIST OF MOST-USED SYMBOLS

A, A_s	System matrices
A_m	Model system matrix
B_m	Model input matrix
C_m	Model output
C_s	System output
D	Damping coefficient
E	Infinite bus voltage (p.u.)
e	Adaptive error
E_{fd}	Generator field voltage (p.u.)
E_q	Internal voltage back of x_q (p.u.)
E'_q	Internal voltage on q-axis proportional to field flux linkage (p.u.)
F	Frequency (p.u.)
H	Inertia constant
i_d, i_q	Armature current, direct and quadrature axis components (p.u.)
j	Performance index
K	Stabilizer gain
$K_1 \ldots K_2$	Heffron-Phillips constants
K_e	Exciter gain
M	Inertia coefficient, $M = 2H$
P	Electrical power output from machine (p.u.)
P_c	Speed changer position
P_d	Operating load of the area
P_G	Power generated

P_m	Mechanical power input to machine (p.u.)
Q	Reactive power output from machine (p.u.)
R	Positive definite symmetrical matrix
r_e	Transmission line resistance (p.u.)
R_s	System incremental speed regulation
T	Stabilizer time constant
T_e	Exciter time constant
$T_{e\ell}$	Electrical torque output from machine (p.u.)
T_m	Mechanical torque input to machine (p.u.)
T'_{do}	Open circuit generator field time constant
T'_{dz}	Effective field time constant under load
T_G	Governor time constant
T_T	Turbine time constant
U	Disturbance vector
V	Lyapunov function
v_d, v_q	Armature voltage, direct and quadrature axis components (p.u.)
v_t	Machine terminal voltage (p.u.)
W	Positive-semi-definite real symmetrical matrix
X	State vector
$\dot{X}$	Time derivative of X
x_e	Transmission line reactance (p.u.)
x_d	Direct axis reactance (p.u.)
x'_d	Direct axis transient reactance (p.u.)
x_q	Quadrature axis reactance (p.u.)
Y	Model state vector

α	Adaptive parameter
Γ	Disturbance matrix
δ	Angle between q-axis and infinite bus
ΔT_d	Damping torque coefficient (p.u.)
ΔT_s	Synchronizing torque coefficient (p.u.)
μ	Adaptive gain
ω_o	Radian frequency
ω_{osc}	System oscillation frequency
'	Superscript denoting transpose
p	$\frac{d}{dt}$
$p\delta$	Speed deviation from synchronous (p.u.)

chapter one

INTRODUCTION

An electric power system consists basically of a set of generating units or sources with their associated prime moving, controlling and protective equipment, a set of energy absorbing elements or loads and the complex network of transmission lines, transformers, switches necessary to interconnect the energy sources and sinks satisfactorily. The prime function of the control system in a power network is to automatically maintain a balance between the real and reactive power supplies and demands in such a way as to maintain optimum system performance.

One of the problems associated with the control of power systems is the off-line analysis, design and optimization of settings of regulators and controllers. Due to the characteristics of the power system, which can be considered a high order interacting multivariable process, basically non-linear with time varying coefficients, it is not possible to specify an optimum set of controller parameters. Up to a few years ago, controllers were designed under the more or less explicit assumption of constant environmental conditions. In marked contrast to this assumption, power systems are characterized by the severe requirement that the system has to operate in a more or less rapidly changing environment, exerting an influence not only on the process to be controlled, but in some instances also on the controller itself. Under such circumstances, the concept of adaptation seems to be an effective tool to eliminate some of the compromises normally required in controller design and system analysis of power systems.

In recent years, a great deal of effort has been devoted to the study of adaptive control systems. The interest in adaptive control systems has been largely motivated by a sizable class of problems for which conventional techniques for synthesizing the controller have proved inadequate. Specifically, a controller having fixed parameters may not be capable of achieving the desired system performance with a given plant. Such a situation may occur when the parameters that describe the plant vary over a wide range of values during the operation of the system (i.e., when the dynamic characteristics of the plant change markedly). To make the problem more complex, the entire system may be directly affected by an environment that varies drastically over the range of operation.

Essentially, there have been two distinct approaches to the adaptive control problem; each in turn, has given rise to a multiplicity of techniques for the implementation of the adaptation procedure. In both approaches, it is assumed that a performance criterion can be defined as a measure of the quality of control. One approach, termed "open-loop" with respect to the system performance, does not directly employ the performance criterion in determining the adjustments of the adaptive controller parameters. The first step, which is generally referred to as the identification problem, is to obtain a description of the plant (e.g., pole-zero configuration, or differential equation). Based on the description of the plant, the adaptive controller is synthesized in such a way as to make the overall system optimum with respect to a prescribed criterion. That is, the adaptive parameters are set at those values according to some computational algorithm, that provide the optimum system performance. In this scheme, the adaptation is based on measurements of the operating environment that are directly related to the values of the plant parameters.

The second approach, on the other hand,is "closed-loop" with respect to the system performance - that is the performance criterion is periodically or continuously monitored and, using this information, the adaptive controller parameters are adjusted to extremize the performance measure. Among the techniques employing the philosophy of performance feed-back, the Model-Referenced adaptive control technique is the most popular. In such a scheme, the desirable dynamic characteristics of the system are specified in a model and the controllable parameters of the plant are adjusted continuously so that its response will duplicate that of the model as closely as possible. The identification of the plant dynamic performance is not necessary and hence a fast adaptation can be achieved.

It is the purpose of this thesis to investigate the application of the adaptive control concept, open-loop and closed-loop to some problems in the power system area. Two problems are considered. The first problem deals with the design of adaptive compensators to supplement static excitation systems. The second problem deals with the deviation of incremental speed regulation with load changes. In Chapter 2, the influence of a generator static excitation system upon the small-perturbation stability of a single machine-infinite system - under widely varying loading conditions - is closely scrutinized in a new way: The dominant eigenvalues of the system are plotted in the complex s-domain for different loading conditions and power factors. Constant real power and constant reactive power contours are shown. The tendency of an unsupplemented static exciter to degrade the system damping for medium and heavy loading is made clear.

In Chapter 3, the design of a variable-structure power stabilizer (i.e., variable parameters) which is altered to compensate for variations in the system active and reactive loading is discussed. An open-loop adaptive technique is adopted, and the optimum settings of the stabilizer parameters associated with a selected set of grid points in the real power-reactive power domain, are computed off-line by minimizing a performance criterion. Whereas a stabilizer with fixed parameters is of necessity a compromise, it is shown that one with variable parameters can offer improved dynamic performance under widely varying load conditions.

In Chapter 4, the Model Reference adaptive control techniques are applied to a classical one-area system. An adaptive controller is introduced to compensate for variations of the speed regulation parameter with loading. The results demonstrate that the adaptive loop is capable of maintaining satisfactory performance.

chapter two

EFFECT OF STATIC EXCITATION SYSTEM ON THE SMALL-SIGNAL SYNCHRONOUS MACHINE DYNAMICS UNDER WIDELY VARYING LOADING CONDITIONS

Modern generators on a power system are invariably equipped with high speed continously acting excitation systems. These are feedback systems which regulate the terminal voltage of the machine. Such systems, using rotating or magnetic amplifiers, have been used for a number of years in the control of generator excitation, supplied by the rotating direct current exciter usually monitored on the generator shaft. The principal functions of excitation systems are[1] :

1. To preserve desired voltage at the terminals of generators and synchronous condensers
2. To retain the load reactive volt-ampere sharing between the paralleled operating generators
3. To prevent excessive reactive volt-ampere loading and loss of synchronism~~s~~ by providing the suitable excitation requirements
4. To increase the system damping and raise the stability limits.

An historical review of the development of excitation systems, the criteria of exciter performance, and the various types of apparatus used in excitation systems is found elsewhere[2] .

2.1 Relation of Excitation System to the Stability Problem

Increased speed of exciter response was one of the first means suggested and applied for improving power system stability. The excitation systems have an influence on the stability of power systems under both transient and steady-state conditions. This influence is clarified by recalling that the power transmitted in a two-machine system is, according to the approximate equation, proportional to the product of the internal voltages of the two machines, divided by the reactance. Therefore, the power is increased if either internal voltage is increased. These statements hold regarding the power at any particular value of angular separation between the two-internal voltages, and hence also for the maximum power. It is also true on a multimachine system that raising the internal voltages increases the power that can be transmitted between any two machines or groups of machines[3]. Therefore, it is apparent that raising the internal voltages increases the stability limits.

Under transient conditions, power is calculated with the use of transient reactances of the synchronous machines and the voltages behind transient reactance (which are proportional to flux linkages). Upon the occurrence of a fault, the flux linkages are initially the same as they were just before the fault occurred. During the fault, however, the flux linkages decay at a rate described by the short-circuit time constant T'_d, which is least in the event of a three-phase short-circuit at the terminals of the machine and is somewhat greater for less severe types and locations of fault[3].

If the fault is sustained for a long time, a machine may survive the first swing of its rotor,but, because of the continued decrease of its field flux linkages, it may pull out of step on the second swing or on subsequent swings.

An excitation system controlled by an automatic voltage regulator causes the flux linkages first to decrease more slowly and then to increase. As a result, a machine which does not go out of step on the first few swings will not go out of step on subsequent swings of the same disturbance. On a more severe disturbance, however, it may pull out of step on one of the first few swings. Accordingly, the action of excitation system during a fault is an important factor in power system stability. The faster the excitation system responds to correct low voltage, the more effective it is in improving stability.

In the steady state, power is calculated with the use of saturated synchronous reactances and the voltages behind these reactances (which are proportional to the respective field currents). If the voltages are constant, the power limit is reached when the phase angle between the voltages becomes $\pi/2.0$ radians. An automatic voltage regulator tends to preserve the terminal voltage constant. If it were entirely successful in doing so under all conditions, the power limit would depend upon the reactance of the circuits between machines, instead of upon this reactance plus the internal (synchronous) reactance. The power limit would be greatly raised by such ideal voltage regulation, particularly if the internal reactance was the major part of the total reactance.

Unfortunately, voltage regulators cannot raise the power limit to anything near the theoretical value just discussed. Due to the delay in the field circuit, the desired restoration of voltage can not always be obtained rapidly enough to increase the electric power in a way to match the mechanical power and thus to prevent power differentials that pull the machines out of synchronism.

It has been found by tests, however, that the use of fast-acting excitation systems does raise the steady-state stability limit a substantial amount[4].

2.2 Semiconductor Electronic Fast-acting Excitation System

As early as 1946[2], a practical experiment was made in the use of a high power electronic device as a utility generator exciter. The device was a mercury arc rectifier. Because of the trouble associated with the use of mercury arc rectifiers (e.g. cooling systems, arc backs, cost), they were not used on a large scale.

With the advent of reliable semiconductor high power devices such as silicon diodes and controlled rectifiers during the 1960's, semiconductor electronic excitation systems have found a significant place in the industry. Consequently, rotating exciters have been replaced by electronic exciters, in which the generator supplies its own excitation through rectifiers supplied from a transformer connected to generator terminals. The exciter voltage is controlled by the use of controlled rectifiers using a signal derived from the generator potential transformers. This type of excitation is a significant advance over previously used excitation systems, in its possible effects on transient and steady-state stability limits, because of its ability to change generator field voltage almost instantaneously. In addition to the basic requirements of a voltage and reactive volt-ampere control on a generator, electronic exciters have a fast speed of response and a high ceiling voltage.

2.3 Types of Electronic Excitation Systems

Basically, two types of systems have been developed using semiconductor devices: the "brushless system" and the "static system".

2.3.1 The Brushless Excitation System

The brushless system shown in Figure 2.1 has so far been confined to thermal turbine generator units. It consists of: (1) a small 3-phase pilot exciter with a permanent

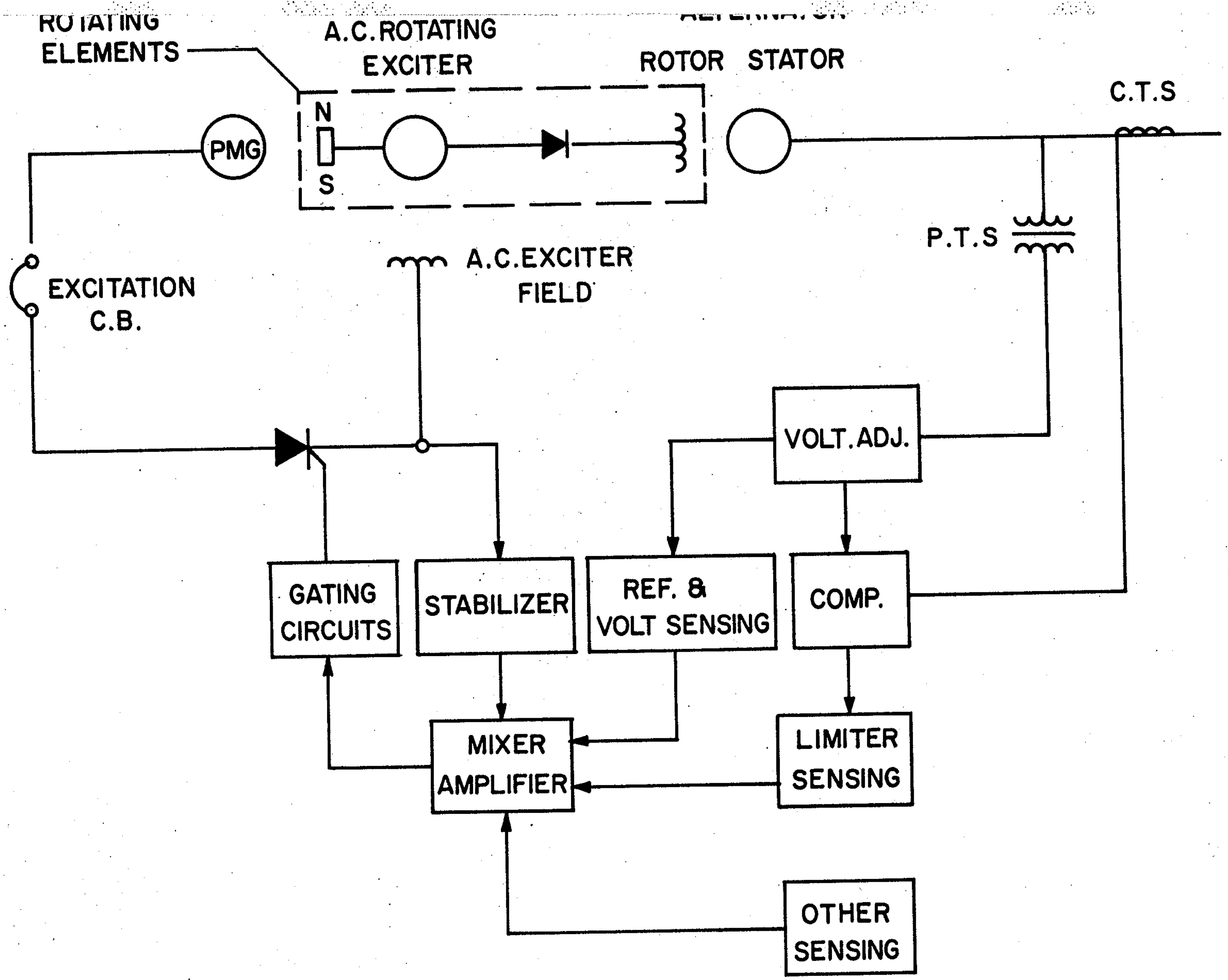

Fig. 2.1 Rotating A.C. exciter with diode rectifier
"Brushless" (After Heeley[2])